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Government/Industry Response to Questionnaire on Space Mechanisms/ Tribology Technology Needs

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PREFACE

In order to obtain a government and industry assessment of whether the current technology base in space mechanisms (mechanical components/tribology) was adequate to meet the requirements of present and future proposed NASA missions, a questionnaire was sent out by Lewis Research Center to government and industry individuals known to be working in the field. The questions dealt with the adequacy of current technology, if they felt an infrastructure was needed to coordinate mechanisms research and what such an infrastructure's functions might be, what types of testing/qualification methods would be needed, and what were the areas where new technology research should to be established.

Approximately 400 questionnaires were sent out in the time frame of February to May, 1990. A copy of the letter and questionnaire is included in the appendix. The majority of the questionnaires were sent to the attendees of the Aerospace Mechanisms Symposium, the remainder to individuals working in tribology. One hundred and thirty questionnaires were returned. The following pages give a compilation of the responses. For three of the questions, there was a yes/no or agree/disagree response requested. For those questions, a statistical compilation is given first, followed by the listing of the respondent's comments.

In general, the responses have not been edited. The names and affiliation of the individuals have not been given with the responses, but an alphabetized list of those individuals responding are given at the end of the report. The responses have been separated into the categories: NASA Responses, Other Government Responses, and Industry Responses.

The general consensus of the respondents was that the current technology base is not adequate to meet the requirements of future long duration NASA missions and that new technology research programs need to be implemented.

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QUESTIONNAIRE RESPONSE

QUESTION (1). It appears that the current state-of-the-art of space mechanisms is not adequate to meet new, long duration, future NASA Space Missions such as the space station "Freedom", a Lunar Outpost, and unmanned Martian Missions. Do you agree?

GOVERNMENT AND INDUSTRY RESPONSE TO QUESTION 1:

<u>RESPONDEE</u>	<u>Agree</u>	<u>Disagree</u>	<u>Not Sure</u>
GOVERNMENT	45(83%)	8(15%)	1(2%)
INDUSTRY	53(75%)	14(20%)	4(5%)

YES RESPONSES TO QUESTION 1

NASA CENTER RESPONSES

(1) Long Lifetimes: It is anticipated that useful operating mechanism lifetimes in excess of 5 years will be required. There is little data available both because few systems have operated for such periods in space and because none of them have been returned to earth for examination. In particular, there is very little NASA-information available on systems employing bearings. The LDEF experiments may cast some light; however, none of these was operational for the full LDEF mission period. The mechanisms that have operated for long periods have been used in fairly benign applications, i.e. quiet environments, lightly loaded and clean. Also close attention needs to be paid to the differences between continuously operating, intermittently operating and storage lifetimes. (2) Thermal Cycling: Normal operating ranges for most applications are quite near room temperature. Although it is likely that space station thermal requirements will be similar to that for most spacecraft, lunar and Martian applications may be quite different with much larger operating extremes and large numbers of quite large thermal excursions.

(3) Contamination: All three environments are likely to be worse than most spacecraft applications. The space station is likely to be a rather busy place and the local environment will suffer from the effects of re-boost, approach by spacecraft, manned excursions and general effluent from a manned structure. The lunar and Martian environments are likely to be especially severe. Large quantities of ambient dust and on Mars, the presence of winds to move them around, provide environments quite different from normal space applications. The lunar dust may be especially bad because of its highly abrasive nature. In addition, the combination of low pressure, temperature and contamination make the environments different enough that extrapolation from earth surface experience is not trivial.

(4) Serviceability: The servicing environment for all three applications may be difficult. Although small systems may be serviceable to bringing them into shirtsleeve environments, large systems will either have to be serviceable in detail in situ or disassembled into modules small enough for transport into a workshop. There will also be a large variety of equipment requiring eventual service. It will be very difficult if not impossible to provide a comprehensive set of spares, manuals and trained personnel. Particular attention will have to be paid to redundancy to allow for delaying repairs, self diagnostic systems, commonality of parts and simplified servicing procedures. On the moon and Mars, maintenance requirements are likely to be high and probably cannot be efficiently

met only by replacement of parts.

(5) Radiation Resistance: Long lifetimes and operation outside the umbrella of the Earth's magnetic field will require materials and parts with better resistance to radiation degradation than those commonly used today. In addition, more information will be required with respect to operational problems associated with high radiation environments, e.g. single event upsets.

(6) Addressing all of the above concerns: Will require a long term technology development program. Because of the significance of the lifetime concerns, early initiation of the program is important to allow adequate time to perform life tests. Manrated hardware, especially safety critical hardware will need to be demonstrated high reliable. Because of the times and distances involved and the high cost of replacing hardware, every effort should be made to provide the highest degree of initial reliability. Providing only large degrees of redundancy will be costly, heavy and may not provide the reliability required.

The increased requirements of the emerging detector and instrument technology cannot be met with existing or untested tribological systems. Temperature radiation, micrometeorite damage, along with 30 year life. Requirements demand a new generation of material/lubrication interaction to be devised.

I keep hearing about tribology-related problems that still don't seem to be adequately solved yet, such as lubricant out-gassing, drawbacks to dry lubricants, drawbacks to sealing ideas, and other problems with materials (e.g. rubber and plastic not holding up in space, metals cold-welding together, etc.)

Data & experience exists but the focus is lacking. Mechanisms need to have the same focus as structures, i.e. viewed as a discipline. Far too much reinvention of the wheel goes on at NASA, at least at GSFC.

Long term failure modes (other than simple wearout) are elusive and difficult to characterize. Mechanisms typically involve a conglomerate of technical areas (e.g., electromechanical, structures, electronic controls, etc.). Redundancy is difficult to implement without introducing new failure modes. Health monitoring is typically sparse, and of a go/no go nature.

Mechanisms containing ball bearings, gears or any components with contacting surfaces currently are having trouble surviving missions of 5 years or less without maintenance.

The structuring of projects does not allow for high enough funding levels up front to provide adequate initial R & D. This is a classical NASA problem. A dollar up front is worth many thousands in the end.

Yes, no experience of vacuum operation at temperature extremes & raw U. V. free oxygen.

The current state-of-the-art mechanisms are not capable of performing reliably for 30 years. I question, however, the need for 30 year life of these components. Why is it not possible to replace the critical long life components? By modularizing these components into 5-10 year life replacable parts we could save lots of R&D money.

There doesn't seem to be a concentrated effort in the area of long duration space exposure mechanisms development at this time. There is a lack of data in the area of long term human exposure to the space environment. There is a lack of EVA STS Missions to gain experience with

hands on different mechanisms.

In discussions during reviews of proposals for space science missions at NASA Langley by the Langley Space Payload Evaluation Committee, of which I am a member, it was generally agreed that there is no basis for vigorous design of mechanisms for long life. What is done currently is to design for 3-5 years life, add some margin in the design, and hope that the mechanism functions for the needed lifetime. This process surely is not acceptable of the long term.

Having been involved in the testing & research of space mechanism at LaRC there is a need for development of Space materials and development of design & testing of mechanical systems such as the recent CEDA system which is presently at JSC.

Current experience with mechanisms which have been subjected to extended space environment exposure is very limited. Typical design life for civil spacecraft and instruments is 2-3 years. Mechanism failures which have occurred are not well understood. If the U.S. truly intends to demand lifetimes of the order of 10 to 20 years for future spacecraft, it is essential that the required design data base be developed. Without such a data base, maintenance repair and refurbishment costs will become astronomical.

Lifetime requirements seem to be the limiter. Non-maintenance mechanisms are not standard, and auto-maintenance isn't a practical solution in many cases. EVA replacement is not popular. Material deterioration isn't well known. (LDEF retrieval will help.)

Space crane articulating joints need mechanical actuator and joint development which can survive many rotating years in the space environment. Lubrication will be a major concern for actual space applications. Heavily loaded joints require some engineering development, but no breakthroughs.

While existing technology has proven capable of reaching and sustaining human life in space for several months, it is still substantially earth dependent and thus incapable of supporting NASA's future new, long duration space missions. The exploration and colonization of space will require new discoveries and mechanisms permitting geological exploration, mining, and manufacturing on celestial bodies sufficient to support human life in space-free of even communications if necessary.

The current Data Base is not extensive enough.

Inadequacy in state-of-the-art technology is primarily an experience base or data base problem. We have no real shortage of ingenious designs. However, we have no real knowledge of how the materials respond to (in a thermal and Mechanical sense) the LEO, Geo, Lunar, Interplanetary, and martian environments. Furthermore, material survivability (fatigue, if you will to distinguish from mechanical response) in the aforementioned environments is also largely unknown.

Yes, I feel the reliability of the current mechanism technology is not sufficient to provide trouble free operation for 30 years. I also feel that the space station environment will be much more hostile to mechanisms than current envisioned.

Yes, while attending the 24th Aerospace Mechanisms Symposium, I became aware that there are many issues that remain to be resolved.

Long term exposure to the space environment degrades most all materials, especially the high performing polymer based composites. New material advancements are needed to reduce this degradation & erosion.

(1) Review of available literature in the KSU library and NASA RECON system does not list space mechanisms as a separate or focused technology. (2) Similarly, the NASA FY91 budget does not carry a line item for developing space mechanisms/tribology for long duration manned space flights. (3) Of seventy DRAPA technology projects for FY91, none are related to space mechanisms. (4) Items 1-3 indicate durable space mechanisms are not treated as separate technology developments but more likely as problems unique to a given project, the solution of which may or may not be applicable to long duration space travel by humans. (5) Based on these findings, and my own experience, I would agree that "state of the art space mechanisms" are not adequate for long duration manned space flight.

It is obvious that any space mechanism can be claimed as "adequate" only after it has been proven successful testing in the designated space environment for the designated duration. The sequence of Space Station/Lunar Outpost/Martian mission will serve the purpose of determining the adequacy of any space mechanism in a progressive manner.

Yes, NASA still uses and relies on components developed & tested for the Saturn V program. Surely, the state-of-the-art has developed new components, maybe better, maybe not, but a new start such as space station, Lunar outpost, etc. should start with a clean sheet of paper. A components competitive test program should be established - Remember mechanisms don't work with components.

Yes, the tribology of many components new used date back to the 1960's. The development of "qualified" components for use in space systems, vehicle and GSE were existing under products which were modified in NASA and contractor laboratories to achieve required performance and reliability. These were tested extensively to prove requirements were met before use. Some of these are still in use in GSE systems for the Shuttle program here at KSC and have performed well with minimal failure rates and maintenance problems. However, I believe new concepts for sealing, reduced friction and advanced materials need to be developed and tested for use in components which do traditional jobs both for one g and zero g applications.

All efforts on space mechanisms have been program driven. Long time goals have been lacking and pet projects have been funded because of the special interest organizations who could afford to lobby for them. Much experience exists at system contract vendors that is not part of the NASA space information pool because of the program based nature of the mechanism efforts. Pure research without a goal does not always produce useful work that is relevant and sometimes duplications short term project tasks without ever having paths cross.

Specifically not adequate for high duty cycle precision motion devices. Bearing design for these applications is still more of an art than a science. New lubricants & materials (ion implantation surfaces, etc.) are available but have not been adequately studied to know what is best for an application. Magnetic suspensions may be necessary for particularly long-lived applications, but then power and electronic reliability problems are substituted for reliability problems. If nothing else, we need better comprehensive life test data on mechanism components.

I believe that many past and current NASA Missions have been compromised by having to use "state-of-the-art" mechanisms rather than developing enabling technology as part of the pre-project activities. I have seen project guidelines that state that no new technology development will be funded by the project. The result of this posture is compromises in creased weight, power, schedule and decrease in reliability.

The requirements for bearing systems to perform to stringent specifications in space for "long durations" is not an easy one to meet, given current technology. Although there are demonstrated successes with space qualified hardware, even these are not without incident (e.g. the Voyager scan platform bearing) The areas that could stand significant technology improvements can be classified as follows:

- a) Tribological understanding of low velocity sliding and rolling element contact.
- b) The further development of long duration, low outgassing room temperature vacuum lubricants
- c) Research into the wear of materials at cryogenic temperatures
- d) Active or passive adaptive control methods of bearing preload under varying load conditions, temperature gradients, and bulk temperature differences.

There is a lack of flight component testing and tear down materials analyses.

The issue is not that current state-of-the-art mechanisms is not adequate, but that our knowledge of long term effects of space on these mechanisms are not fully developed.

Yes, from the Power Systems point-of-view. At this point power systems that last 30 years for Lunar or Mars applications have been mentioned but there is no design for them yet. Therefore the mechanisms to be used in this systems are not being addressed in any of the existing programs yet.

OTHER GOVERNMENT AGENCY RESPONSES

A 10 to 12 year life is not attainable using current technology. Much of this has to do with the manner and priority by which current mechanisms are designed and constructed by prime space craft builders.

Tele-robotics must be developed for high performance as both a teleoperator (man-in-loop) & robotics (full autonomy). Mechanical demands are opposing. Teleops must be low friction, low inertia, easy back driveability for good force-reflection and low operator fatigue, with little concern for backlash. Robots conversely, must have zero backlash and high stiffness, with little concern for friction & backdriveability. Therefore some mechanism must be developed that will meet both these demands w/o impacting the performance. Telerobots are needed for all.

No Lubricants last > 10 years without replacement.

Materials/lubrication systems inadequate to support long durability mechanical components under harsh environments. Current technology may last less than a year.

INDUSTRY RESPONSES

We can't design systems reliably for 30 years life on Earth so how can we do it for space? Need to overdesign space systems and build in extensive redundancies

Thirty year life is long even on Earth. Long term space mechanisms with require both integration of advanced technology and the creation of new technology.

Much of the mechanical components "know how" that existed to put a man on the moon is no longer available. There needs to be a steady support for continuing maintenance and development of the technology base.

I have observed lubrication failures on reaction wheels in just over 5 years. Even a 7 year life for reaction wheels presently does not seem possible. Currently there are wide industry discrepancies in appropriate lubes for deployables. There is little or no documented successful, flight experience and everyone has their own black magic formulations for lubrication.

There is great deal of cross-disciplinary programs, apart from space mechanisms yet to be resolved.

I know of no lubricated mission component to have lasted more than 14 years, either because the spacecraft became unusable & was turned off or some non-lubrication connected failure occurred. Thirty year life has not been demonstrated.

Long duration reliability under severe environmental conditions is beyond current state-of-the-art.

The Alpha and Beta joints are one obvious example.. how to make such large bearings in such critical applications and have them operate properly for 20 to 30 years? What lubrication approach to use? How to tell the one you've chosen is correct?

It is obvious that we lack the capability for a 30 year mission! For our products the limiting factor is lubricant life.

More research and development is needed in robotics, spacecraft modularity, space operations, and large deployable space structures.

Typical space application for bearings/lubrication has shown maximum life of 10 years. Wear, seal degradation, and radiation effect for a 30 year life pose significant challenge.

Limited long duration orbital environment testing has been done or planned. We on Hubble space telescope have a 15 year life requirement and it has been very difficult obtaining adequate funding to do long term testing, That is, tie up a dedicated environmental chamber including personnel to staff it. Accelerated testing was relied on heavily but that leaves some uncertainty when one might expect long periods of inactivity of the orbital hardware.

Information on lubes is needed to provide lower coefficients of friction, longer life and less outgassing. More information is needed on the adequacy of synergistic coatings. Longer life motors are needed. The use of ceramic bearings needs to be studied. One time, low shock release mechanisms need to be developed. The use of composites, plastics & other none-metals

needs studying.

I agree the current state-of-the-art technology of space mechanisms is not adequate to meet new, long duration, future NASA missions. The majority of existing and past space mechanisms have been designed for short life cycles. Design life has usually not exceeded five years. Space mechanisms' components and lubricants have been designed to this short life.

Our present capability is based upon a 30 year old technology that has been "stretched" from benign 6 month life needs to difficult 10+ year life Missions. We have a great deal of catching up to do.

There is no established base of test data that supports a 30 year life. This is particularly true in the environments associated with the stated objectives. Life analyses is not a well organized discipline, and will not be acceptable without test backup.

The effects of long term exposure of mechanical components, especially mechanisms, to space environment requires questionable extrapolation.

Lack of technology and experience in design of light weight, long duration, dexterous mechanisms for space applications.

We should note the advanced robotics in use by nuclear power plants which utilize the remote handling of nuclear fuel or of nuclear weapon laboratories for safety and reliable manufacture of nuclear weapons and triggers. Another "space" -inner space deep diving submersibles have remote mechanization requirements.

A review of the past 5 years of mechanism papers submitted to the AMS reveal little new in design concepts, but rather a refinement of existing components and concepts. This is also true in the field of "soft engineering" such as reliability and assurance testing. It is not surprising since there is little commercial advantage for R&D for such limited applications and production. The two specific areas that need attention are ultra-reliable actuators and new approaches for long duration storage auxiliary power systems not utilizing electrical energy.

Sputtered MoS₂ has a very short life, and baked on MoS₂ often must be put-on too thick for some close tolerance applications.

Future mission requirements of reproducible precision pointing (<1 microrad), low jitter (<0.25 microrad), small thermal gradients across bearings, long life, low mechanism weight and reciprocating oscillatory travel place severe demands on Tribo materials, structural housing materials, surface modification and lubrication techniques. Stat-of-the-art designs and components have serious limitations that restrict performance and thus cannot meet the above requirements. Consequently, to satisfy the stringent requirement of future NASA space missions, a new coordinated space mechanism initiative is needed.

Assuming that space mechanisms operate in the vacuum of space, there have been to my knowledge no tests or demonstrations that lubricant systems will last for 30 years. There is indication that some of the lubricant systems used on the Shuttle may break down over relatively short time periods.

Not many new designs due to shortage of R&D funds.

Probably. Answer is based on recent quest for info on low coefficient of friction films for low temperatures, low pressure applications. Very little seems to be known or available.

Familiarity with design of space mechanisms indicate that a central reference library of space qualified generic components is not accessible. What data that does exist is derived from tests of hardware designed for limited functions. Many factors affecting life or space and hostile environment is not documented.

There is no concentrated effort on the part of NASA or private industry to perform the basic research to compliment the design efforts in aerospace mechanisms. Every company requires their own specialists who do not have time and funding to be a resource for advanced systems.

In the absence of oxygen, protective films cannot form on the asperity surfaces at a rubbing interface. Therefore, mechanisms that depend upon solid/solid or boundary lubrication of rubbing surfaces will wear rapidly due to adhesion. Use of classical lubricants fails because of the low temperatures. Also erosion of exposed surfaces by high velocity particles appears to be faster than was previously suspected.

The operation of any space mechanism requires proper lubrication, the lubrication technology applicable to space conditions is not adequately developed, especially for long-duration operations.

Lubrication, especially with solid lubricants, is large an unproven technology for > 10 year lifetimes in LEO and Deep Space Mechanisms. Minimum wearing surfaces (Minimum debris shedding), whether lubricated (low friction) or unlubricated (controlled friction) are required for in-vacuo use.

Need development work in following areas-

- Long life Bearings in space environment
- Long term lubrication systems
- deployment mechanisms

Present designs are not oriented to long term space exposure and subsequently do not provide assured reliability for long term utilization.

Most current systems are not designed for a 30-year life.

Tribology data used for space mechanism design is difficult if not impossible to obtain and if available, is either not applicable or extremely outdated (Apollo Era). Many company libraries no longer carry documents over 20 years old, however articles published today regarding space mechanisms are so highly specialized as to be of no practical use.

A life cycle of many contemporary tribosystems is much lower than the 30 years of scheduled life of a space station "Freedom". For example, life of an air conditioner compressor is only 10-15 years.

Shortage of investment by Defense and Co's for advanced material sciences.

Yes, in our opinion it is not the mechanical components per se that are inadequate but the materials engineering associated with surface finisher and lubricants.

Our confidence in designing the actual mechanisms for spare station is high but we will accompany the development phase with considerable materials testing.

Yes (1) the environment on the moon is different than in space therefore, one needs to design and deliver systems comparable with 1/6 g, dust, and wide temperature swings. (2) On the surface of Mars we now have 1/3 g, dust but wind driven, wind loads and wide temperature swings. (3) On both surfaces there is a need for long life, reliable mobile systems (Rovers)

Yes, Mechanical systems wear down due to sliding & rolling friction. New, innovative, non-wearing systems must be devised.

Yes, the answer is yes, but; as engineering manager for the development of the Flight Telerobotic Servicer end of arm tooling, I see a simple, effective & robust system (i.e. FTS) coming on line before 1995.

Yes, designing mechanisms and lubricant to last 30 years in a space environment is a new requirement to SSF and future space missions. Consequently, a very limited data base exists that can be used by designers to develop long life, low maintenance, reliable mechanical components used in a space environment.

Yes, very few mechanical components in the tribology area such as bearings and seals, have been so far proved to be durable and reliable for a service life of, say, 5 or 10 years. To meet the mission goals, it require major development efforts.

Yes, tribology is not adequate for mechanisms in long duration space exposure if they cannot be serviced.

Yes, reliability record to date it too inconsistent. Some great successes, some notable failures.

Yes, I believe that ceramic materials can be utilized in many instances where "fretting corrosion" would be a problem for metals. However, the use of ceramic materials, and the data on it's behavior and characteristics, have not been widely published.

Yes- (1) Space based robotic mechanisms must be developed, made reliable & lightweight.
(2) Automated docking & refueling umbilical mechanisms must be developed
(3) Reusable soft landing mechanisms
(4) Automated, smart lunar vehicles

Yes, lack of long term experience in the hostile environment of space (>10 years). What will be the "lessons learned" for such missions? Durability of materials and lubricants? Hardware mortality and redundancy?

Yes, I do agree with your position, although I do not believe that major problems lie in a lack of technology. I believe that in order to successfully complete 30 year life, new space mechanisms must not be designed based on "old" style mechanisms, but must rely on new concepts in reliability, redundancy and back up systems.

Yes, 30 year life machinery (continuous operation) is not easy to achieve in earthbound applications. Cryogenic refrigerators, thermal engines, and dynamic seal pumps all have limited seal wear life and limited bearing life. Solid lubricated mechanisms are the most widely used design approach, and all solid lubricated systems have limits to lifetimes because they wear continuously in operation. Alternate bearing and seal technologies are needed.

Yes, we continue to have significant problems on earth itself with our GSE mechanisms - then in earth orbit with rather simple mechanisms (such as the recent problem with the Hubble telescope solar arm deployment). Our problems are initial/developmental and after long usage (wear-out and/or deterioration factors). We have yet to study or do extensive research in equivalent space situations and environments.

Yes, bearing life is limited by the life of the lubricant. To meet 30 years, considering that it is not practical to test for 30 years, and because of the uncertainty of acceleration factors on lubricant life, it is necessary to design predictable oil or grease supply systems for continuously operating devices such as: gyros, CMG's, reaction wheels, momentum wheels, despin bearings, gimbals, drives.

There are no 30 year Earth systems existing, which makes space design even worse.

Much work needs to be done to establish improved bearings. Current designs are inadequate for many spacecraft applications. The latest in materials technology is slow to get into real bearings (such as ceramics, CVD coatings). There is an inadequate level of tribology study with new bearing materials.

How do you automate solar dynamic systems on the moon for generating power and processing heat. There are questions of what mechanisms would work in this environment and what would be the tribology, vacuum, dust, and low gravity, etc. effects.

NO RESPONSES TO QUESTION 1

NASA CENTER RESPONSES

- a. Some communications satellites are achieving a 10-year life
- b. We don't really know how much their life can be extended
- c. Lubrication of reaction wheel bearings is a probable area of difficulty in reaching 30+ years of orbital life, but I don't think one can definitively say that current designs are not adequate.
 - i.e. longer life oil reservoirs could solve this problem.

No, some mechanisms work for station was done for earth orbital environments. This work will not be appropriate for the environments on the surfaces of the moon & Mars, where gravity, soil, and atmosphere or mars will drive the requirements for technology.

No, with a proper design & development along with redundancy systems, the current state-of-the-art of space mechanisms should be adequate to meet new long duration missions - the problem is how to keep the lubrication between moving parts from breaking down over along period of time.

The currently existing body of engineering knowledge in both the areas of mechanisms and tribology is adequate to design for long duration, future space missions. There is an extensive wealth of demonstrated successful applications for long term lubrication of rotating and articulating components on several earth orbital and deep space missions to support a sound engineering design using existing engineering and materials data bases. The challenge is the judicious and sometimes non-obvious application of this knowledge.

I am not aware of any requirements that can not be met NASA with current technology.

Both the Space Station and the Lunar Outpost will be manned during the periods wherein all mechanisms must function, therefore, the need to produce a mechanism/tribology that functions for 30 years is alleviated in that the only rationale for having the manned presence is to provide maintenance and repair as well as to perform functions that would be very complex otherwise. It will be much more economical as well as more functional to provide redundancy for the manned missions than to be required to provide 30 year life mechanisms.

We are currently having difficulty developing space mechanisms for applications requiring very long life and very cold temperatures. Mechanisms wouldn't have to be at temperatures below -70C and maintenance could be performed on them, i.e., lubricant reservoirs replenished and bushings replaced.

We have the technology to do a lot. The problem is we want too much. We try to design a Cadillac when all we really need is a Volkswagen. We spend too much money & time doing "Phase---" studies, writing specs, etc. We need to stop writing specs & building!!!

INDUSTRY RESPONSES

No, I think almost all of the needed mechanisms are out there or could be developed by extensions of technology and/or design with proper commitment (Space Mission Technology Initiative?)

No, solutions can be worked to problems I am aware of.

No, Present mechanical systems are meeting their design lives of 7 to 10 years. Technology exists to extend this to 30 years when required. It is only a matter of lubricant storage capacity or utilizing magnetic bearings which are developed. Roll rings can replace slip rings to meet 30 years requirements. The remainder is just designing it for the desired life.

No, I would suspect any shortcomings in these areas are due primarily to materials and their behavior in space and not mechanism, although new materials certainly could require new design techniques.

No, the current state-of-the-art technology is not necessarily being employed in today's Space program. The Space Shuttle system's technology is 20 years old. The adequate use of new technology in developing enhancements in existing programs and developing new systems have been hampered by the utilization of resources in maintaining the status quo. In summary, the technology to achieve the above goals exists with some problems to be resolved, but is not being applied. Resource commitments to establish long term goals is missing.

Foil bearings using polyimide bonded graphite fluoride coatings will be used in the air lock compressor for the space station. Bearing life specification is for the full 30 years based on a 10,000 start-stop requirement. Bearing life is based on start-stop since no wear occurs at design speed. Foil bearings have shown life in excess of 100,000 start-stops.

There is nothing lacking in the state-of-the-art of mechanisms, or their component parts, such as torque motors, bearings, gears, electronics, etc. for space applications requiring very long duration operation. The problem is getting the designs into test very early because hydrodynamic lubricating films will be required over boundary lubrication and only real time (you cannot use accelerated life testing on hydrodynamic lubricated mechanisms) testing can be done under simulated load & temperature cycling. If you want to design a mechanism to last 30 years you will have to life test it for 30 years (real time).

Current state-of-the-art is, by its very nature, developed to meet whatever current requirements exist. As the need for new space mechanisms occurs, and one could assume that will take place overtime, new technology and design concepts will certainly be developed. Today's mechanisms were developed to meet today's needs. Tomorrow's needs will be met using tomorrow's technology.

If this philosophy had been applied prior to the Apollo Moon landings, we would still be studying the problem, rather than benefiting from our successes.

I designed the steering system, hand controller, and brakes for the lunar roving vehicle in 1969, while working for the Delco Research Ctr. I was only 29 years old at the time. If we could do it then, we can do it now. Mechanisms don't usually last 30 years without some form of maintenance (even on Earth).

The state of the art is adequate for these missions, but certainly far from fully mature. A great deal of work is not required, particularly for a long-term lunar colony. Emphasis is needed upon locating and exploiting in-situ the mineral assets of the moon. Most of the problems of a long-term orbiting station are tractable with current technology, although many of the solutions will be by brute force nature. I assume that at present a long-term colonization of Mars is not regarded as a realistic prospect. Lessons learned on the moon will be a logical introduction to this.

Maintenance should be part of any cost effective program. Not many things here on Earth run for 30 years without maintenance.

We need to combine studying lubrication systems (wet vs dry) for bearings and other rubbing assemblies. Currently Bray 601 grease is accepted "norm" for bearings, I would like to see studies on metallic dry film lubricants that do not "leech out" like MoS₂.

I have three problems with the statement: (1) NASA's problem is more a matter of lack of definition, lack of adequate long-term planning, and finally a lousy procurement system that frequently selects the wrong contractor to build the system. An example of a better approach is what the Canadians did (are doing) on their SS program. Lack of commitment, lack of planning is our problem. (2) The lack of focus within NASA also hurts the efforts, i.e., every center has its own "hobby shop" where they expend a lot of time and money play with new technology. Little if any of this effort ever gets used on real programs because the real programs are in a different part

of the organization. If these bits & pieces of effort were focused on a single effort it could produce a really effective effort to accomplish something, however, this would have to be connected to a specific program to solve a real problem rather than just random research. (3) In the US (with our system) the doers are in our industry not in our government agencies (like NASA). This means that NASA's role should be to define goals, establish standards, co-ordinate, administer govt funds, etc., not spend big \$ in-house activity. All this in-house money is wasted because in the end industry is who build the hardware anyway. If this course was followed NASA would be leaner and more effective, and the money so released could be used for other, more productive efforts, which would be connected to the real programs.

YES/NO RESPONSES TO QUESTION 1

INDUSTRY RESPONSES

I personally feel the technology is available. The problem is where? We need more widely circulated models for life prediction and performance predication. I feel that such models exist (wear, torque, etc.) but that the computer models are not widely available.

The answer is perhaps. Short cycled mechanisms such as deployment actuators would have no problems. However, continuous functioning mechanisms such as solar array drives and momentum wheels spin bearings will likely have life problems before reaching 30 years. The fact is that no one has flown mechanisms for 30 years (about the time since the space era began), so the electro-mechanical and tribological reliability of certain mechanisms is in questions. For example, our operational experience with attitude control gyro bearings spans about a dozen years.

Yes and no, thirty years ago, most actuators were hermetically sealed, but for the past 10 to 15 years most are not because the life requirements were only 1 to 15 years and history showed that an unsealed actuator could survive. The longest Harmonic Drive life is currently being established on Pioneer 10 & 11, which is a scan platform stepper drive. Pioneer 10 was launched Feb 1972 and both 10 & 11 are sealed drives. Therefore, the state-of-the-art is adequate, but may have to be "dusted-off". It is another matter to extend the life of the current mechanisms to last 30 years.

Can't answer: Don't know: New Req'ts. Isn't it your job to establish the fuels?

The first two words in this question, "it appears", suggests the originator of this questionnaire has already performed an evaluation of the current state-of-the-art of space mechanisms and does not believe it to be adequate to meet advanced space mission requirements. The development of any adequate mechanism to perform a specific function is a consequence of the recursive application of the DESIGN, FABRICATE, IMPLEMENT, TEST, EVALUATE loop associated with any good development process. Adequate mechanisms exist today to justify such ambitious endeavors as listed in questions 1. In terms of Space Station Freedom, one only need spend an adequate period of time becoming familiar with the direct development to date of software and hardware tools/mechanisms specific to space station design to realize the primary block to its (FREEDOM) initial implementation is funding.

QUESTION (2): Is there a need for new or improved space mechanisms technology development?

GOVERNMENT AND INDUSTRY RESPONSE TO QUESTION 2.

<u>RESPONDEE</u>	<u>Agree</u>	<u>Disagree</u>	<u>Not Sure</u>
GOVERNMENT	51(100%)	0(0%)	0(0%)
INDUSTRY	65(96%)	3(4%)	0(0%)
TOTAL	119(98%)	3(2%)	0(0%)

YES RESPONSES TO QUESTION 2

NASA CENTER RESPONSES

Yes, there has not been a mechanisms program, per se, in Code R for at least a decade. When the Space Station program was first initiated, enabling technology was assessed and defined. Mechanisms was suggested as an early technology thrust, but dropped. Some (very few) elements were put under other thrusts (e.g. roller drives).

(a) See question 1C for an example. (Lubrication of reaction wheel bearings is a probable area of difficulty in reaching 30+ years of orbital life, but I don't think one can definitively say that current designs are not adequate. i.e. longer life oil reservoirs could solve this problem.)

(b) Modification of existing designs will be needed to stretch out the expected lifetime.

Yes, we design space mechanisms for short life spans several week to 3 years max. in space. When we try to extrapolate to longer periods problems arise.

Yes, there is always a need for new or improved space mechanisms technology development in terms of materials, lubrication, etc.

Some major problems, such as tribology related problems, still exist which prevent us from being able to launch a mechanisms that can operate in space for 2 or 3 decades.

There is a need for life testing of common components such as bearings.

Modeling tools are limited and operational techniques such as "signature analysis" have not generally been implemented.

In the area of wear on components. Improved materials, material treatments and lubrication are required to provide better wear characteristics of mechanisms' components.

Many new materials are discovered each year and fundamental research is inadequate to develop the technology. Space lubrication is always a problem. This area should be addressed.

I believe there will always be need for improving mechanisms. (Make them smaller, lighter, more

reliable, etc.). I certainly do not believe we have achieved a level of technology in this area where we can simply say "ok, we have perfected this science, Let's move on to something else now."

A system of solving mechanisms problems before the need for a solution becomes absolutely necessary would prevent operational delays.

There is always a need to improve on existing materials, mechanisms, and tribology data bases. As new endeavors are undertaken, new requirements are identified. The big difference is that what is now available is adequate for all currently identifiable needs. This does not mean that this knowledge in these critical areas should not continue to be enhanced on a continuing effort to prepare for future needs which as yet have not been identified.

This is particularly true in the robotics area. There's a need to develop sophisticated robots (i.e. manipulating arms, hands, etc.) to assist or even execute the assemblies of various structures as well as carry out experiments.

The primary issue which needs to be addressed is to substantially improve the reliability and durability of space mechanisms. There also exists a need to develop new mechanisms which fully exploit advances in micro-processors and control systems to perform repetitive tasks and which possess some degree of adaptability. Eventually autonomous mechanisms will be required. These mechanisms will have to be capable of self-diagnosis, and be repairable or refurbishable by robotic servicers.

New technology is needed for the space crane.

While many useful space mechanisms and tools and the basic materials required to design and make them are known, man is still essentially tied by an umbilical cord to earth for the life sustaining essentials of oxygen, water, food and shelter. Technology will be required to develop most if not all of the essentials in space if the planned space missions are to succeed.

To develop a more reliable database.

The mission foci which will be required as applications for mechanisms technology include Space Station Freedom, Lunar Base (which have some unique challenges), the Mars Mission(s), and the Global Change Initiative satellites, currently EOS. All these missions are long term and intensive of either manned or robotic manipulations of material. Some of these devices for manipulation will no doubt be very flexible due to severe mass restrictions and so must be describable analytically in order to effect viable control. As a consequence mechanisms must be designed and fabricated which have virtually no free play. Therefore, design requirements must include almost no free play in addition to verifiable long life.

In future space exploration I think it is essential that the best possible materials be used and the best engineered and designed mechanical systems be used. This will be accomplished by establishing a research and development program to obtain these goals.

I think improvements in bearing/lubrication, drive and pointing systems can be made which would prove beneficial to long-life programs.

There is always a use for new and improved technologies in mechanisms and tribology. Each new program brings with it a new set of problems and solutions. The saying that invention is 10% inspiration and 90% perspiration is very perceptive. The greatest gains would seem to come from trying to adapt the current technology to a new problem and by making small adjustments to make it work more efficiently. Invention is not something that can be dictated nor can it be scheduled. to plan a major program on the necessity for major new break through is folly.

A need exists for new and improved mechanisms for current and future space transportation systems. Some work (Advanced Launch Systems Technology Developments) is being accomplished to improve existing launch systems but is not sufficient and in most cases not applicable to long duration manned space exploration. Work should begin immediately to survey and catalogue past and present government civil and foreign developments for possible use on future programs such as the Human Exploration Initiative (HEI). Of particular interest are success stories such as the Voyager program where durable mechanisms were developed that are still working after twelve years in space. On the other hand, "lessons learned" from failures are extremely valuable in avoiding similar problems in the future. Other than ALS, there is little evidence of space mechanisms technology developments to improve current launch systems operation or to meet the rigid survivability requirements for prolonged manned deep space exploration.

Yes, NASA still uses and relies on components developed & tested for the Saturn V program. Surely, the state-of-the-art has developed new components, maybe better, maybe not, but a new start such as space station, Lunar outpost, etc. should start with a clean sheet of paper. A components competitive test program should be established -Remember mechanisms don't work without components.

Yes, many new unique jobs for the future programs will dictate components and systems to do traditional 1g jobs in zero g such as propellant transfer, inspection and repair of systems remotely, etc.

Life sustaining equipment should be put in the highest priority in the manned spaced program. For long duration and harsh environment space journey, at least a triple backup system with an independent mechanism should be provided. This will not only help to secure the success of the mission, but also help to increase the psychological stability of the astronaut during the long, lonely journey. Mechanisms adjusting astronauts to different gravitational environments are extremely important. It has been proven that the human physiological process varies in different G's such as the "strength" of bone etc. The energy efficiency of current space mechanisms should be improved. The development of "in-space manufacturing" mechanisms should be made a high priority to provide the flexibility of meeting unexpected challenges in new environments and to utilize the local material.

I personally have never found a source for practical application information. Most good mechanisms people are self made experts at their jobs. No rewards come to people who find simple solutions to problems and everyone wants exhaustive technical reports to support a position or finding before it can be used. When the solutions are project need oriented no such reports are cataloged for general distribution. Most companies consider such information to be semiconfidential and the reason for their being experts in their field.

- (1) I believe there is a big need for some unified and/or standardized mechanical & electrical interfaces, to that end the system modularity would be enhanced.
- (2) Much more forethought should be given each device for an orbit maintenance and repair by either an astronaut EVA or a semi-autonomous telerobot system. Ease of repair & maintenance should be a high priority during design. Extending the life span is one important goal... but ease of maintenance, repair or replacement on orbit should be another.
- (3) The present overall systems are far too complex and inherently prone to failure.... designs should be streamlined with common approaches between similar companion technologies.

Yes, especially as they relate to mechanisms for instruments and spacecraft that must operate under cryogenic temperatures. Few mechanisms can meet the performance and life specifications of missions such as the proposed Space Infrared Telescope Facility (SIRTF)

There will be many new mechanisms needed and many improvements required. Any innovation change requires much development in order to be qualified for space flight. Development will additionally be needed to implement human safety features and to lengthen lifetimes.

Vibration isolation systems, the dampers which are presently available are inadequate for many specific uses.

See responses in previous question. Also there is a need to develop new surface coating technologies in particular for bearing applications.

Yes, it is not certain how lunar environment and Mars atmosphere could affect such mechanisms. Therefore a technology development program that address such issues should be initiated.

There is always "need" for the development of new and for improved mechanisms. The ability to preload deployment mechanisms and to design erectable space structures such that either type is thermally stable and exhibit linear response is important to our ability to characterize long-term structural response. If we are unable to adequately and accurately make such predictions such missions as are mentioned in question (1) would be jeopardized.

There is a need for both technology and knowledge development. Again long term effects are not fully appreciated.

OTHER GOVERNMENT AGENCY RESPONSES

There is a need to give spacecraft designers and builders improved technology to work with. However they have to be convinced that the mechanisms will work. To convince them much of the emphasis should also be on accelerated or long term operation to build a confidence base.

Mechanisms must be developed that provide higher torque density (2-3x better than SOTA), low friction with no backlash, high stiffness for real time control. Kinematics that provide flexible configuration and high dexterity are needed for maintenance and assembly operation, long life and serviceable by telerobots.

Need sealed for life lubrication. Need design criteria for durable mechanical components under harsh environments.

INDUSTRY RESPONSES

Of course there is a need for new and improved mechanisms, just as there is a need for new and improved jet engines, materials or structures. Mechanisms and actuators that are lighter, stiffer, longer-lived and smoother are always sought. Specifically we are concerned about vibration from gimbal actuators, CMB's and other moving mechanical assemblies exciting booms or other structures supporting critical sensors or antennas. Since launch cost can run as much as \$50,000/lb., weight is always an issue. Making parts out of lighter and stiffer materials, such as beryllium and graphite composites raises other mechanical and thermal concerns. Specific mechanism needs are identified under question 6.

Yes, there is always a need for lighter weight stronger and/or more capable mechanisms.

Yes, need more development & life/service tests on mechanisms

Yes, advanced tribology is the key to improving mechanism lifetimes in space. Lubricant performance data is, however, sketchy. A systematic (scientific) approach is needed to map out the capabilities of current lubricants and to point to the characteristics needed in improved lubricants. Most current data is out of the public domain and is application specific.

(1) Yes: the environment on the moon is different than in space therefore, one needs to design and deliver systems comparable with 1/6 g, dust, and wide temperature swings

(2) On the surface of Mars we now have 1/3 g, dust but wind driven, wind loads and wide temperature swings

(3) On both surfaces there is a need for long life, reliable mobile systems (Rovers)

Yes, Mechanical systems wear down due to sliding & rolling friction. New, innovative, non-wearing systems must be devised.

Yes. (1) IVA low disturbance automation

(2) Stiction problems with conventional mechanisms in vacuum

(3) Increased integration of two fault tolerant designs into mechanisms, particularly with respect to inadvertent release of a workpiece

Yes, technology development will provide a data base to assist mechanism designers in the design and development of a multitude of different types and sizes of mechanical components.

Yes, in the bearing area, long life bearings, such as magnetic bearings, require substantial development to make them suitable for space applications.

Yes, almost every case I have seen regarding tribology is unique. Long term uses are highly suspect as to reliability.

Yes, majority of items developed to date have been for mission of limited duration. In general, the industry as a whole does not know how to design long life into mechanical components for the space environment.

Yes, uncertain confidence in low speed oscillating rolling element bearings in vacuum. Would like to see long term testing program results with various lubricants/coatings.

Yes, to say otherwise would mean that everything we have currently is adequate to meet untried space challenges.

Yes- to support elements of #1 (Space based robotic mechanisms must be developed, made reliable & lightweight; automated docking & refueling umbilical mechanisms must be developed; Reusable soft landing mechanisms; Automated, smart lunar vehicles)

Yes, improved only in the sense that life tests should be started now to prove the designs will run for 30 years.

Yes (1) Develop means of sharing technological innovations that include such things as "lessons learned" during development, long term exposure test findings, and a database of proven mechanisms technology that can be used as a foundation to build from.

(2) Establish a list of mechanisms technologies that need to be developed in order to support future space goals. Assign priorities and estimated R&D cost expenditures.

(3) Define testing programs that will provide the aerospace community with the capabilities to design long term space missions.

Yes, previous & current designs are still accepted with single fault tolerant components.

Solid lubricated mechanisms are the most widely used design approach, and all solid lubricated systems have limits to lifetimes because they wear continuously in operation. Alternate bearing and seal technologies are needed. Some resources should be applied to innovative new mechanism technologies such as magnetic levitation bearings, flexures, electronic scanning, etc. Not just more millions into more and more "friction, wear, solid lubricant materials development".

Yes, for the past 15 years, the emphasis has been on using PROVEN designs in order to keep the cost down and win contracts. These designs were not necessarily the most advanced i.e., Honeywell's roll ring design (vs. slip rings) has never been flown. Only roll rings have a chance of meeting a 30 year life...reliably.

Since the life of a Harmonic Drive is based on the life of it's wave generator bearing, any new technology in bearing materials and coatings would be a great improvement. I'm thinking of hybrid bearings (metal raceways & ceramic Balls), all ceramic bearings, high-tech thin film coatings for the raceways such as Diamond Black (B₄C), etc.

Yes, we continue to have significant problems on Earth itself with our GSE mechanisms - then in earth orbit with rather simple mechanisms (such as the recent problem with the Hubble telescope solar arm deployment). Our problems are initial/developmental and after long usage (wear-out and/or deterioration factors). We have yet to study or do extensive research in equivalent space situations and environments.

Yes, knowledge builds upon knowledge. The use of today's technology would make available actual data that could be used as building blocks to gain further knowledge. As stated above, today's technology is not being used in practice. but still resides in the lab. We can go no further until that technology is functionally tested. The problems with constructing a lunar outpost and maintaining a manned presence is a prerequisite to a Martian mission.

Research and Development is always inherent to the establishment of new technology. The reason for the answer of MAYBE is because of the ambiguity as to the degree of closed loop feedback associated with research and development, technology definition, product implementation. To date, a literature survey would reveal a hiatus in current applied proven technology and unapplied new technology. One primary reason for this hiatus is a space structure is made of many systems, themselves comprised of many mechanisms. The mechanisms utilized are those available at the time of design and costing. The elapsed time from fabrication to implementation is so lengthy that initial mechanisms are obsoleted by the availability of new technologies that have developed over the elapsed period. These new technologies/mechanisms can not be utilized due to too great an impact on the overall bought and sold initial design. Numerous examples of this dilemma can be found in the Trident and STS programs. The real trick is to have a design that can take timely advantage of CURRENT technology; ie, technology exists, implementation is lagging.

Yes, lube supply systems are needed. Mechanisms should be serviceable or replaceable and/or redundant.

Designers should consider all alternatives on how to best transfer force and power before concluding that mechanical components requiring relative motion are the final answer. In other words, don't make solids roll or slide against one another unless absolutely necessary. What this really means is that tribologists must be involved in the initial design rather than being brought in as an afterthought. Second, we must learn how to run reliable accelerated tests to prove out new bearing/lubrication systems.

Long term missions requirements along with the necessity of reliability, go beyond current proven technology.

I've only been exposed to this topic via the 22nd Aerospace Mechanism Symposium, and every idea that was present there has been used for years. For the things to be done in space what more is needed?

Space technology, like any other technology, relies on a broad base support in education, technology maintained at universities and by applying this technology on an ongoing basis. One can not simply turn-on technology after 20 years of no support.

Such areas as precision pointing, active damping, vibration isolation, and reduced weight need to be addressed. Also better material usage is needed and improvements in motor magnet energy product.

Search studies that look into long term space exposure, durability, reliability as well as characteristics inherent to a weightless environment, have shown that research has not been advanced to a sufficient level for some of the objectives to be fulfilled.

New technology development is needed to verify models.

The following are needed. 1. Thirty year fluid or dry (or unlubricated) systems. 2. More likely, we need a relubrication method, as automobiles have, so that astronauts could perform preventive maintenance. (Grease guns & Zirc fittings come to mind.) 3. Higher reliability non-brush type motors. 5. New rotary electrical joints to replace ring and wiper type slip rings, potentiometers,

encoders, etc. 6. Vastly improved speed reducers (better than harmonic drives), something better than worm/worm gear reducers. 7. Permanently lubricated plain spherical bearings. 6. Any technique for lubricating roller bearings. 8. improved seal materials (rad. resistant, low friction, etc.).

No long term test data exists.

There is a need to be able to demonstrate lubrication schemes capable of keeping mechanisms operating for the duration of the mission. I think there are plenty of Mechanisms as such, but tailoring their design to meet the life requirements combined with all the other mission requirements is the challenge.

If we are to attempt such long duration missions, the technology must be developed.

Long life space mechanisms need to be developed.

High temperature, low friction and wear coatings would help foil bearings in power systems applications. also effect of contaminants on solid film lubrication would be helpful.

There is definitely a need. While we may be able to characterize the space environment very well by current standards, our knowledge of the effects of space exposure on materials will continue to improve, permitting us to do a better design job. As we develop the requirements for future space endeavors, it will be necessary to solve new problems with new solutions.

Yes. Lubrication, Seal development.

Of course there is always need for improvement.

I believe there is a critical need for new or improved space mechanisms technology development. Space mechanisms' components and lubricant systems must be designed to accommodate longer life cycles. In addition, research must be conducted to develop new state-of-the-art mechanisms for common spacecraft applications. Recent spacecraft designs have emphasized the use of proven, previously qualified mechanisms to reduce costs and provide schedule compatibility. Some of these mechanisms are more than fifteen years old. It is difficult for companies in the aerospace industry to develop new mechanisms due to the competitive bid process. The government should lead independent research and development programs to develop a new generation of space mechanisms.

We are facing longer life (10 years), higher and lower temperatures, higher loads, and new materials to lubricate. To save weight, parts become smaller and stresses increased.

Mechanisms have to be developed as part of the overall system, too often the requirements are component rather than system oriented. For a 30 year life, mechanisms have to be totally redundant, autonomous in operation and totally fail safe. Bearings and devices requiring lubrication need methods to be developed that accurately monitor their health both autonomously and interactively to ensure that lubricant supply is maintained.

Simplification of components to reduce weight. increase reliability and ability to function in a space environment.

How could any engineer answer this in the negative? It is an unspoken act of faith among engineers who take their profession seriously that technology must continue to advance or the human race will by default start a slide back into the dark ages. If the question is why space mechanisms as distinguished from any others, the answer is that in developments for space the penalties for inept work are the most severe. Development aimed at space applications will stimulate the most creative human efforts in any field including mechanisms. That these will spin off to benefit the entire race goes without saying.

Automation and robotics in one-g environment has been basically "automation." Significant accomplishment has been achieved in the area of software and electronics development. Little effort has been made in mechanical and mechanism systems development, especially for performing complex and unplanned space tasks.

The technology of tomorrow will be better and the need to develop that technology exists today.

We should not be ignorant of already developed hardware and systems used in the nuclear industry and deep diving submersibles.

A central location where engineers can readily obtain all current test data, on all aspects of mechanism design (lubes, gears, bearings, coatings, etc.) would be very beneficial.

As discussed in question 1, there are three specific areas that need improvement: actuators, long-duration storage power systems, and improved reliability and testing techniques. The key to success is government funding of very specific studies addressing advanced space mechanisms requirements. Good work has been done in this area by Dr. E. Bean of PRC in McLean, Virginia for both the Navy and NASA-KSU.

If we sign-up to men living in space as a goal, then mechanisms, coatings, materials, lubes, etc. all become very crucial. However, if we say that what we have achieved today is ok as far as manned shuttle operations, and no need to go a step further, then I see no reason to go any further with technology research.

To satisfy the requirements listed previously, developments in designs, bearing, surface modification and lubrication are needed. Current mechanism designs often include redundant actuators, are heavy and do not have efficient provisions for thermal control or lubricant refurbishment. Bearing technology needs development of lighter, fracture tough ceramics, ceramic matrix composites and high specific strength Ti alloys. Surface modification technology needs to be advanced to eliminate coating adhesion limitations and provide increased penetration of implanted atoms. Current lubrication technology limits life of bearing systems due to loss of liquid lubricants and degradation in a vacuum-wear environment. Solid lubricants possess low load carrying capability, restricted endurance lifetimes and extreme environmental sensitivity. The limitations in all of those areas synergistically control the performance and life of mechanisms, which cannot meet the requirement for future missions.

We don't have the technology today to say with confidence that mechanisms can be lubricated for 30 years.

Longer life and lower maintenance will be required.

Aerospace metal/ceramic/composites industry needs info/data/techniques for applying low friction coatings for low temperature service. Metal-Matrix composites for space structures. Shape-memory alloys for joints/connectors. We (industrial castings for aerospace applications) need better understanding of hydrogen-resistant metal castings for use in launch systems.

Much of the existing data does not address mechanism life beyond 5 years. Hostile environment affects have not been incorporated with existing data. A central library accessible to the space industry is mandatory

Space mechanisms in and of themselves have been used in many systems. What is required are materials, processes and tribology models that can verify the designs. A library of these mechanisms is in the NASA domain. There have been 24 years of "Aerospace Mechanisms Symposiums;" held under the auspices of NASA. These are all the mechanisms you need to build on.

Without this technology development, metal surfaces of space mechanisms can not be allowed to rub unless it is at low speed, and if replacement is possible, this will have to be done on a frequent basis. This will severely restrict space mechanisms design.

For expanded space explorations, there is a definitive State need for improved tribology technology.

Lubrication, especially with solid lubricants, is largely an unproven technology for >10 year lifetimes in LEO and deep space mechanisms. Minimum wearing surfaces (Minimum debris shedding), whether lubricated (low friction) or unlubricated (controlled friction) are required for in-vacuo use.

Efficient RWA/MWA designs needed for:

- Power/Weight efficiency
- Balance Loads (Rotation)
- New Ball Bearing technologies
 - Retainerless designs

Present designs are not oriented to long term space exposure and subsequently do not provide assured reliability for long term utilization.

There is always a need for such development.

(1) Replacement of a malfunctional or aged tribosystem under space conditions can be technically or economically prohibitive. Accordingly, design and technological improvements are necessary to meet a 30 year life for tribosystems. (2) A grandiose program of space exploration requires review of all current expertise in tribology. Specifically, it relates to problems of wear and non-fluid friction. Despite the substantial advances made in this area during the last 50 years, the phenomena of wear, seizure, scuffing, fretting, galling and dry and semi-dry friction have remained basically in the scope of empirical disciplines. Furthermore, the available empirical data often are in contradiction among each other and more often they are not available at all. It is believed that now with a launching of the Martian mission it is time to conduct a massive theoretical and experimental overhaul of the scientific and technical data, and conduct wide scale friction/wear tests of the engineering materials in controllable conditions. Special attention should be paid on

scuffing which may appear in both lubricating and non-lubricating conditions, since it would be a leading factor of wear in space as it relates to conditions in a deep vacuum. One should note that the modern low friction vapor deposited or ion implanted coatings are usually too thin to provide a long lasting protection. At the same time, the available low friction ceramics may change their properties during their lifetime.

There are real needs but they must be focused and connected to real programs not just on research.

The state-of-the-art technology assessment for components/tribology is poorly defined.

We need greatly expanded knowledge of ceramics and surface modifications as it relates to bearing tribology. Until we do this work, end users won't accept our revolutionary materials.

NO RESPONSES TO QUESTION 2

INDUSTRY RESPONSES

We have successfully designed, tested & flown despin bearings on dual spin spacecraft that have demonstrated 10 years plus life. Real time testing of these bearings have completed 10 year life tests. Also, slip ring assemblies used in these devices show little wear over 10 years of testing and lifetimes of over 20 years have been projected for these slip ring assemblies. The technology is here now. All we need to do is to initiate early design implementation studies to get these mechanism designs underway and into test.

No, it will happen as a result of solving specific problems to achieve viable designs. Establishing a separate task of technology development has historically been un-productive.

No, until you identify the mission and demonstrate current techniques are insufficient. How can you say there is a need to develop new techniques. My best guess again is that its going to be more of a materials problem than a design problem.

YES/NO RESPONSES TO QUESTION 2

NASA CENTER RESPONSES

When you're not funded to study an issue its tough to say that it is an issue

QUESTION (3): What would be the benefit of a coordinated space mechanisms technology program? How would you benefit from such a program?

NASA CENTER RESPONSES

The nature of this specialized field is not amenable to "forced" improvements by expanding larger amounts of money annually. The way to achieve improvements in mechanisms technology is to design, build and flight test actual mechanisms needed for space missions. Each requirement is very unique. I doubt that I would gain much from a centrally coordinated program.

A coordinated program would yield faster results and better utilize our resources

A coordinated program should include technology development and transfer mechanisms to allow its inclusion in actual applications. The research effort should therefore be done in conjunction with the development which houses the actual requirements, needs & specs

Learn about the DO & DON'T on certain applications, don't have to reinvent the wheel. Information on development are usually of benefit.

Some duplication of effort could be avoided and someone could monitor what is being worked on vs. what isn't and encourage others to work in the neglected areas so that everything that needs to be ready at the same time can be. Also communication is a benefit of coordination, as well as a requirement for it.

It can provide the data of life tested components that individual projects don't have the time or money to invest.

The benefit would be training for new (and used) engineers, a database of materials and components and their applicability, standards for mechanism dynamics, software and analysis methods, cross training in electronics and mechanical systems.

Would aid in the development of design approaches and instrumentation techniques that could lead to very long-life mechanisms (i.e., performing the function/task required). Effective redundancy means could also be evolved for space missions. Equally important, the placement of "mechanisms" in organizational structures would become better established. Presently, it is a much battered area and "falls through the cracks" among endless squabbles of "is it a subsystem", "is it a structure," etc. This tends to result in the final design of mechanisms occurring in a crisis environment.

A program consisting of tests to improve life of mechanisms' components and distributing this information to mechanism designers would be beneficial. One problem now is knowing what developments have been made already and always having to start from the beginning because information on mechanism developments is not well circulated.

Far too often, NASA contracts out the work and depends upon the sub-subcontractor to provide the optimum tribo-system, when they probably use 10 year old technology to be safe or worse yet- "Profitable." Look to ESA!

Space flight programs have a tendency to only use hardware and techniques which already have an extensive heritage of space flight use. In addition, monetary and schedule constraints often preclude the development of appropriate advanced technology. A long range program to encourage advanced developments will pay large dividends. Some new money will be required, however a great deal can be accomplished by coordinating efforts among many projects. A development program which is too expensive or too risky for any one program may be perfectly feasible when several programs share the risk and cost. In addition, there is insufficient sharing of knowledge between NASA centers. It is likely that many costs could be avoided if there were better knowledge of the work being done across NASA and the DOD. As new technology is developed to meet the needs of the long term occupation of the solar system it will be especially important that the information is disseminated as widely as possible. If this is not done, the pace of development will be slowed and the "wheel" will be re-invented many times.

We gain a great deal from the aerospace mechanisms symposium. I suppose this would be an extension of that. Perhaps just more support of it would help. I have a great deal of trouble getting NASA/GSFC to send more than one person from my branch to this. In some years -none.

These types of programs are always difficult to set up and to manage, and are usually under used. By increasing technology transfer between companies, agencies and countries, much time and money can be saved by eliminating redundant research and development efforts.

This would be an excellent way of identifying what is currently available to all potential users. Since we are engaged heavily in structures and mechanisms work, such an effort would be directly beneficial.

The development of space hardware, software and the NASA-integral product of combining both to produce active mechanisms to be used for space missions. The spin-off benefits would include: the development of new combinations of materials and structural designs with applications on Earth: the development of new control systems (i.e. computer algorithms, data structures, etc.) which would also have applications on Earth.

A coordinated program would eliminate duplication and provide the most effective means for technology dissemination.

Communication of current technology! There is an awful lot of "stuff" out there that I tend to run across by accident. Coordinated, open communication would help everyone solve their problem.

More efficient use of resources, by reducing duplication. Can also divide work so that centers, etc. can work in their areas of expertise.

A coordinated program would eliminate redundancy and allow a broader range to be investigated. This would provide me with more knowledge in a shorter period. A better way to document mechanism work would be good. I frequently find that I can get little or no data on mechanisms that have flown. The ASM is a good source of info but the steps to publish a paper are time consuming and difficult. If we had a way to put out a short description and limited data into an electronic database for others it would be great. The quality of the papers is not very important.

The principal benefit would be the establishment of a much-needed technology data base, the need for which is apparent to design engineers who are asked to execute long-life designs. Extraterrestrial mechanisms, such as might be found on a lunar-based crane, impose other design difficulties which complicate long life design, namely the dust or dirty environment. These particles obviously cause wear much more quickly than in the clean space situation such as would exist on or around Space Station Freedom.

Everyone would gain from a coordinated program. A broader span of knowledge could be obtained by using everybody's input. I could benefit by using new improved materials, better testing methods, and more confidence in the use of these mechanical systems.

Focused effort, efficient use of limited resources.

IF, and I repeat, **IF**, a coordinated space mechanisms NASA-technology program could be accomplished, it would mean that many solutions would not be invented time after time for different problems. The current situation exists because there is so little communication in the space mechanisms field and everyone tries to do it all on their own recognizance. A truly coordinated program could benefit in the same manner that group actions such as brainstorming generates synergistic results. However, the formation of such a group is much easier than the sustaining efforts which will be required to keep it going, and to get peers to use it. Our history has not been encouraging for such efforts. NASA has formed many such committees in the past and to my knowledge few of them were worth the effort and the time required to formulate the committee and its charter.

- It would more clearly define the needs.
- It would increase communication. This could ensure that all needs are being addressed while minimizing redundant work.
- It would spur interest and encourage work on this area.

First, a coordinated space mechanism technology program will be more efficient and thus less costly. Second, the desired overall goals will be accomplished sooner. Third, the resulting proprietary technology can be more easily licensed thus assuring an even greater benefit to the participants and consuming, tax paying public.

A coordinated program -- coordinated being the key word -- would firstly identify the absolute state-of-the-art to engineers and designers who may not spend all of their time working on these types of mechanical devices. A coordinated program would keep NASA from duplicating work or re-inventing the wheel. As a design engineer, I would benefit most from a mechanisms data base run from a personal computer. The data base would describe the device, give specifications and provide expert points of contact for further information.

I think all of NASA would benefit. It would be excellence training for the young NASA engineers who must design, test and maintain systems to support NASA's missions.

Interaction promotes idea development and exchange of information can save considerable time and money. Benefits would be in the application of new designs with more cost effectiveness to the program.

(1) Such a program would provide design information, test results and performance history to designers of mechanisms for long duration human exploration. It would also highlight short-comings in technology. (2) We would benefit by being made aware of new and modified technologies being developed by others to improve both ground and space based operations. (3) The program should have as its goal, giving the user clear visibility into all space mechanisms under development.

History has proven that combined thoughts are generally more "complete" than single thought, although they may be less efficient. However, among the people involved in different stages of development, the coordinated space mechanisms technology program definitely will help them to know what they should do to link their product to that of others. In our environment as vehicle launching and payload processing industry, we will benefit by increasing our efficiency in processing and lifting the payloads.

Better and easier system integration

Avoid re-inventing the wheel

More modular designs, easier maintenance & repair

Reliability, more refined and historically proven devices

Shared knowledge base

As in any such program, the benefits of coordination would reduce the cost associated with redundant development due to lack of information regarding similar research and applications. Realistically, however, private competing companies will consider much of their most innovative research in space mechanisms proprietary. This should be accommodated by the government programs in areas that are away from basic research and closed to specific mission applications.

If coordination means open and organized access to developments, plus funding for development of new components it could help tremendously. Presently, in order to develop a new component (such as the MiniDual Drive Actuator or Wax Pellet Actuators or Shape Memory Metal Actuators), Projects must fund the efforts. This results in components that are tailored to a project rather than generic and results in disjointed development as projects are postponed or cancelled. Additionally, little effort or funding is available for communication of designs.

Unless the investment is committed to be substantial and continuing nothing much will happen. Pure technology will not help much and the needs have been around forever. You can state it any way you choose but we are talking about a mature technology that needs refinement and modification to be application specific. Catalogs such as the "lubrication Handbook for the Space Industry" form a starting point of reference, but have not been updated for so long they gradually become useless.

We could develop industry with standards for bearing/lubricant design & selection. Also, electronics parts development would make more standard parts available for class S applications. (Class S resolution-to-digital converters would be nice to have.)

The benefit of a coordinated program would be to identify and fund in a prioritized manner thus yielding maximum return at minimum cost with a good understanding of schedule risk. The benefit to engineer in the mechanisms field would be that he could get enabling funds prior to project start thus minimizing development risk/project schedule.

There is a need for coordinated development of standard materials and processes.

Each center works on their specific tasks. A final configuration coordination would be required, but isn't that taken care of in the specific project's management?

Pro:

- less costs for one agency
- knowledge of other programs
- complementary programs
- avoid overlapping of efforts

Con:

- depend on others
- no direct authority on other programs
- cooperation (?)
- control/direction of technology

Benefit on systems level must come from advocate - you. I don't know how I could benefit specifically. Obviously, the country/NASA would benefit from having the correct technologies in place.

The largest benefit would be the generation of a "pool" of space qualified mechanisms (mechanical components & tribology) which designers/program managers would have at their disposal.

A coordinated program would provide a critical mass of expertise to bear on the technology. It would also bring to fruition the advancements at a greater rate than now. Probably at a reduced cost to the government.

OTHER GOVERNMENT AGENCY RESPONSES

New technology development, New materials, new design guidelines.

One program cannot necessarily do everything and a well coordinated effort could build on the strengths and successes of the other efforts. Also, coordinated efforts will allow emphasis to be placed on several different mechanisms. I firmly believe that great benefits come from coordinated programs.

Higher performance actuators would have immediate application in: space robotics, nuclear robotics, environmental clean up robotics, and industrial robotics. Higher reliability would be great interest to space and nuclear robotics.

A storehouse of test proven component information would be extremely valuable. Many times we spend a lot of time and money re-inventing the wheel.

INDUSTRY RESPONSES

The major benefit would be that corporate R&D funds would not have to be expended solving tomorrow's problems. NASA should be looking down-the-road at mechanism technology to be needed 5 or even 10 years from now for NASA's missions. Where is the next generation of space

lubricant going to come from? The next generation of space actuator?

None - adding another layer of government would only impede the progress of U. S. Space technology and advancement.

(1) Cross-fertilization of ideas, (2) Less "reinventing the wheel"

Get systems (both integrated & subsystems) into production sooner with more confidence

It would be highly beneficial if the results could be efficiently disseminated - as, say, a computer data base. It would save reinventing the wheel every time and enable smaller companies to have ready access to the benefits of the country's R&D effort.

I don't want to make stupid mistakes as conceiving power systems.

A sharing of information is crucial to the success of future, long-term space operations. We keep reinventing the wheel. Usually, someone has already solved a problem we encounter but without communication, we start from scratch.

The benefit would be to address deficiencies list in #2. My firm would benefit because we are in the space mechanism business and we have industrial clients to whom spin offs will aid.

A direct benefit would be less development testing if a technology data base existed.

A coordinated space mechanism technology program will enable pulling all the resources together, making the technology development better planned and more cost-effective, establishing a technology data base available to U.S. industry, and maintaining U.S. space technology lead among world competitions. As a product manufacturer, we will know better about what technology resources are available and what new technology items can be further developed.

It has been my experience that every company does its own research quite frequently duplicating the effort of other companies. Common research and data basing could eliminate this and reduce overall costs.

Access to design information - what has worked in what situation in the past.

Research costs lower if duplication is eliminated, and all users could benefit from results

Because space mechanisms are so unique, so undeveloped, and in such small demand there is not enough private R&D. Our experimentation is driven primarily by market analysis. Breakthrough technologies are seldom found in chasing existing markets, they are offshoots of other work.

- Very highly integrated control, power and diagnostic chips for "smart" mechanisms
- New electric motors that use 28 voc without life-limiting brushes or costly, complex brushless motor drives
- Modular mechanisms that can be built-up to suit various applications
- Modular fluid systems that can be integrated, maintained and reconfigured in-situ

The benefits would be directly related to who ran it and how it would be run. I would benefit by having testing performed to prove to everyone how well and how long out equipment will run.

Certainly compiling all of the accumulated experience and lessons learned in one place would be very useful. I suspect the only other benefit to me would be if I got a job working on such a program.

(1) Coordinated exchange would decrease the number of redundant development products, increase the maturity (on ↓ load time) rate of new systems, and would identify those technologies that need extra attention in order to meet the planned mission goals and timelines.

(2) Reduce design/development time due to having an established database of mechanisms technologies to build from and by avoiding the "lessons learned" by others.

The benefit of such a program if implemented properly would be the exchange of new design concepts between centers. Also this program should actively encourage interchange and sharing of technology. This is very much lacking in the current NASA structure, especially in space station activities.

A "coordinated" program implies too much central control of research & development. A more beneficial approach would be a coordinated effort to distribute available funding to research agencies on the basis of proven successful developments; not the credentials of staff and investments in exotic lab equipment.

It would help prevent duplication of effort. What does NOT work and WHY NOT is most important.

We would share in the use aspects of technology so developed. All would benefit. The degree would be related to the number of our specific problems "studied" in the program versus the total in the program.

The program should minimize as much as possible one of a kind applications. The LRU concept has been beneficial in the Shuttle program, but little, if any, interchangeability of unmanned programs have been established. This is due to different manufacturers of different rockets, and different specifications between manned and unmanned programs. A coordinated program would allow for more continuity in the manufacturing sector to meet specific needs and standardized specifications and allow more flexibility in the joint use of facilities, parts, fuel, etc.

The answer to this questions falls from the answers to questions 1 and 2. Coordination is the flow controller associated with the product/mechanisms development loop referred to in answer 1. The benefit is timely evaluation of current mechanisms development and fabricated with current technologies and the consistent application of evaluation results.

Program should define requirements, develop solutions, conduct tests & disseminate information. We could use results for air force satellites.

The biggest benefit would be the spinoffs to more mundane, earth-based systems. This was demonstrated repeatedly during the 50's and 60's when space exploration was more popular than it has been recently. A technical capability invariably comes up with more useful general solutions than a mind which looks only within a narrow constrained area.

1. Creation and implementation of technology needed to complete a mission objective. 2. Renewed focus on Agency missions. 3. Stimulation of gov't, university, and industry technology in the area of precision and reliable mechanical systems which will have immediate impact on national competitive posture in commercial industries (machine tool, robotics, transportation, etc.)

Would help to concentrate on technology not on competition. We would like to be a part.

Will maintain and expand the "know-how" base. We would benefit in two ways. 1. Support for maintaining an expand the base, and 2. expanding our own "know-how" by association with coordinated programs.

1. Centralizing Information. 2. Centralize findings to reduce duplication. 3. Prioritizing needs.

New mechanisms for long life would require a lot of new materials, lots of testing. Benefits would include. 1. Obtaining some of the work. 2. Possibility of commercial exploration of new devices and new materials with well documented performance. 3. Personal, corporate pride.

The following would be very helpful. 1. Long life seals, 2. lubricants, 3. establishment of appropriate derating factors, 4. Radiation tolerance, 5. Contamination tolerance.

The benefit would be in using the ever-shrinking funds to develop useful data applicable to a range of mechanisms by lots of designers. For example, in long-term space exposure, what happens to lubricants? or wear Bearing materials? or real materials? Is atomic oxygen really a concern? How serious a problem is lubricant evaporation in contaminating optics. Can guides be put together on allowable distances? We (Battelle) would benefit from participating in the research and also in applying the results to our ongoing space projects.

Lower ultimate cost. We would benefit by not having to repeat work already done.

It would be a source of information and testing that could definitely benefit our products. It would also aid in the transfer of technology between private companies and the government, and between companies themselves.

It would help us focus on prioritizing issues, provide better communications, new ideas, materials, and the transfer of technology.

Coatings with lower friction, longer life and higher temperature capability. My company would benefit by broader application of longer life, higher reliability systems.

Design and test data for mechanisms exposed to very long real time life tests would be beneficial to the entire industry because such testing is rarely done due to late arrival of the test results and the expense of the test (requires long term commitment of vacuum chambers, personnel & test support equipment). Presently, we "fly & fix" which is totally inappropriate for the space station, lunar or martian bases. Almost all our problems with mechanisms are related to poor initial design and an inadequate test program to detect deficiencies.

A possible benefit would be consistent and wider dissemination of mechanism concepts, test results, mechanism requirements and failures. It would also encourage dialogue in the community of mechanism designers, I would benefit by finding out about failures and things to avoid.

Better management of limited resources to focus on key areas as dictated by the industry goal. Technology transfer to the space & ground applications.

A technology program would use available money for studies and leave less for real programs. I would agree with it though if it only addressed lubrication life.

It could preserve a lot of resources to eliminate parallel duplication of effort, i.e., re-invention of the wheel.

I'm sure many aerospace companies spend too much time and money on mistakes, failures and "reinventing-the-wheel" when developing mechanisms. A coordinated program would help to minimize these effects. A coordinated program would act as a central hub to develop, collect and then serve as a focal point where designers could go to for specific advice, concepts and/or help.

Money would be better spent designing particular mechanisms to do particular jobs.

The benefit of a coordinated space mechanisms technology program would include improved performance using new technologies. Advanced mechanisms' costs could be reduced if the performance requirements can accommodate a variety of space vehicles. Space vehicle program costs would be reduced assuming development costs would be shared. As a space vehicle mechanisms and configuration designer, I would benefit because a coordinated space technology program would allow me to select a mechanism design from a database with the confidence that the design would be reliable, incorporates the latest technologies and would be cost effective. I would also be able to consult with knowledgeable, experienced experts about space mechanisms.

There has been a strong need for such a program for over 10 years. We now have many good candidate lubrication systems that need development. The benefits would be developed and tested improved lubrication systems ready to use. We could use these now!

I do not believe that a coordinated program as such would be beneficial. However, coordinated specs from the customers and strong long term IR&D programs should lead to the development of "standard" long life devices that have been thoroughly tested under "realistic" environments.

We would be able to base any future designs on factual S&O information, reducing speculative designs, redesigns and thereby cost.

I assume that a "coordinated" program is one in which problems are identified by communal effort and redundancies avoided among agencies attacking the problems. This is obviously an intelligent way to organize a program. My work would benefit from having fertile fields of endeavor pointed out to me and from the assurance that I was not replicating someone else's efforts.

Development of space mechanisms technology requires very specialized expertise and continued government support. My current activities in support of NASA/JSC are in the development area of robot friendly mechanisms, smart fastening methods, and ground and flight assembly and maintenance demonstrations. Development work in other areas such as long duration lubricant and seals in hostile space environments will certainly benefit our design and development tasks.

An improved database of information regarding materials performance. Perhaps a line of pre-

qualified actuators and bearings. An "off-the-shelf" line of mechanism components would save any program from qualifying costs.

Cost avoidance of duplication of developments pioneered by the nuclear industry.

Access to all relevant data. Cross-pollination of all design approaches would save money or "duplicate designs." Engineers can learn from one another's mistakes, and experiences.

A coordinated space mechanism technology program would AMS provide a clearing-house for information on existing hardware and would also provide a forum for discussion of requirements and techniques. Since I am a consultant and developer of kinetic devices, this arrangement not only would keep me current but also provide a method of making inputs to the program.

I work for the mechanisms area of Hughes Aircraft Company Space and Communications Group, so space mechanism breakthroughs of any kind are important to me.

A central, coordinated space mechanisms program would provide a means of developing generic as well as a program specific technology base that could be repeatedly utilized. Such a program would prevent wasteful re-design and duplication of effort. As a result, more resources could be applied to technology development that will advance the state-of-the-art.

At the present time there is a fair amount of information generated about space mechanisms, but there is no coordinated program to gather and disseminate the information. Often the mechanism designers don't have a good knowledge of the state-of-the-art. ASLE and others have done good work in the area of lubricants, but their efforts aren't necessarily directed towards space. I see their publications only rarely. On the other side of the ocean, the Europeans have been actively pursuing Space Tribology for some time. I believe that any mechanism designer needs the best sources of information.

Wouldn't have to reinvent the wheel.

We will benefit for this planet work, especially regarding superconductivity machinery components, which also require service at low temperatures and low pressures. And will benefit in the future, in our manufacture of metal parts for vehicles on extraterrestrial missions.

Hopefully a coordinated space mechanisms program would result in a coordinated central library of applicable mechanical components which have been fully characterized under a continuum of space environment. If not continuous, at least the circumstances of unavailable information would be documented.

A tribology laboratory would be an enormous resource to begin with. The "Aerospace Mechanism Symposium" library would be a resource that catalogs all various mechanisms. These centers, ably staffed, could be a valuable resource for future systems in that they could establish material specs, lubrication requirements, future hybrid structure and materials, etc.

In general, un-manned machinery in space could be made potentially maintenance free with a properly coordinated technology program. For our company (pump manufacturer), development of new materials (base & coatings) and then new surface lubricants or other anti-wear technologies could allow practical product-lubricated bearings (currently only possible in special

situations in small, lightly loaded machines) and better life of annular seal surfaces.

The development of the above-said tribology technology could not be effectively carried out through individual efforts. A coordinated program is needed to bring together the related talents and to focus on specific goals. As a tribologist and a researcher, I can benefit from such a program by taking advantage of the channel to contribute my skills, and by broadening my contacts with colleagues.

- (1) Focus attention on needs. (2) Assure adequate effort devoted to technology.
- (3) Assure non-duplication of efforts

Address specific mission needs such as the Space Station and deep space probes.

The ability to concentrate the technology would be the chief benefit of a coordinated space mechanisms technology program. The Shuttle program could be a direct beneficiary of this program.

We could more easily integrate our technologies with current applications.

Redundant work could be avoided, risk in programs mitigated.

It is believed that the benefit of a coordinated space mechanisms technology program would have the same or even more profound impact on science and technology as early investigation of C.A. Coulomb. The following are some specific benefits which are expected for the compressor industry and for any other industry producing machinery with movable parts:

- Reliable methods for prediction of friction, wear, friction temperatures, contact characteristics, stick-slip friction and other related parameters.
- Technology for development of wear resistant materials.
- Verified information of the friction/wear properties of the current construction materials.
- Software related to optimization of the friction interfaces.
- Tribological properties considering a transition to new refrigerants.

Developing advanced lubricants and other special materials.

A coordinated program would provide a critical mass of expertise to bear on the technology. It would also bring to fruition the advancements at a greater rate than now, probably at a reduced cost to the government.

We need "technology" less than real, well planned, long range programs to serve to focus the available expertise. In short, the technology is already here, it is the lack of what to use the technology on that is missing.

Piloted Rovers technology is in need of improvement.

If properly structured and funded it would increase the activity level in R&D of bearing tribology and give the activity more focus and direction

QUESTION (4): Do you feel there is a need for NASA to establish a Space Mechanisms Technology Infrastructure in order to:

- (1) Coordinate new technology development?
- (2) Develop standards for U. S. Industry use?
- (3) Furnish consultancy and advisory services?
- (4) Maintain a comprehensive data base on capabilities/solutions?
- (5) Maintain adequate testing facilities for U. S. Space Interests?
- (6) Facilitate the transfer of space technology?
- (7) Encourage cross talk between government customers?
- (8) Insure coordination of NASA and DOD research?

Should any areas be added or deleted to the above list?

GOVERNMENT AND INDUSTRY RESPONSE TO QUESTION 4.

	<u>YES</u>	<u>NO</u>	<u>?</u>
(1) Coordinate new technology development.	113	10	1
(2) Develop standards for U.S. Industry use.	76	39	9
(3) Furnish consultancy and advisory services.	96	19	9
(4) Maintain a data base on capabilities and solutions.	118	3	3
(5) Maintain testing facilities for U.S. space interests.	106	10	8
(6) Facilitate the transfer of space technology.	117	4	3
(7) Encourage crosstalk between government and industry.	113	6	5
(8) Insure Coordination of NASA and DOD research.	115	6	3

NASA CENTER RESPONSES

Coordinate new technology development- yes, however, this program need not be extremely expensive or all encompassing. An appropriate approach would be a NASA wide equivalent to the Director's Discretionary Fund with encouragement of government/contractor cooperation. In addition, proposals for small scale very advanced work in specific areas could be solicited with a winnowing process at successive stages to select the most promising and fund them for further development. Cooperative development efforts for new technology between many projects should be encouraged. Large scale development should be done in the context of a specific application.

Develop standards for U.S. Industry- no, this is an activity best transferred to NIST or one of the professional societies. NASA is likely to be best served by identifying a need and funding these activities in another organization that already has the expertise and the charter.

Furnish consultancy and advisory service- yes, but this function is likely to be best served by establishing a data base and sponsoring symposia. It may be appropriate to create NASA Fellows whose charter is to do fundamental investigations and developments and serve in the consultancy

and advisory role.

Maintain a comprehensive data base - yes, this activity is much needed. At present, the generation of engineers that powered the moon program and much of NASA's early success has retired or is nearing retirement. Access to much of the technical heritage of the agency and its contractors is limited by there not being a central "card catalog" of the information that exists in these peoples' heads and file cabinets. This should be the highest priority of the items mentioned. It could be funded through NIST or one of the existing technical database services.

Maintain adequate testing facilities for U.S. space interests- yes; the type of environmental testing needed is likely to require facilities beyond the present capabilities and beyond those feasible for one center, program, or project to set-up by itself. Existence of an agency test facility, especially if the services were provided free for appropriate test programs would substantially expedite the initial stages of new technology development. Such facilities could be most cheaply created by augmentation of existing facilities at NASA centers coupled with an appropriate budget for test support.

Facilitate the transfer of space technology- yes, this function can be met through the data base discussed above, the existing tech brief system and the sponsorship of symposia. A large benefit could be obtained if travel funds could be made available for attendance of these symposia by more NASA engineers. At present, attendance is sharply restricted by the limited availability of administratively controlled travel funds.

Ensure coordination of NASA and DOD research- yes. This is likely to be the most difficult area of all due to the veil of secrecy likely to descend on very advanced technology. NASA's and DOD's needs will overlap substantially and the cooperation is well worth pursuing. Substantial benefits can be realized in this area through the data base development. Cooperative efforts are likely to follow spontaneously if the different groups know what the others are doing.

An infrastructure would help the development of some range of standards for "spaceflight qualified" components which would foster the participation of more industries not now supplying spaceflight hardware. We now tend to look to the established Aerospace companies for everything.

The above categories lists the needs far better than I can. On a scale of 1-10 (10 being most needed), I rate all of them an 11. Recent "challenges" due to contractor oversight have led to rush decisions and half completed work.

The test facilities exist. The problem is overcoming the barriers for their use.

The principal reason for the negative answers above is that a NASA LaRC informal and effective forum on aerospace mechanisms has existed and held annual meetings since 1965. The Aerospace Mechanisms Symposia (AMS) are jointly sponsored by NASA centers, Lockheed Missiles and Space Co., and Cal. Tech. The meetings rotate among NASA center which publish the papers in a NASA CP document. The AMS, originally organized by pioneer mechanisms designer, Dr. George Herzl, serves as a point of interchange for designers of their actual hardware problems.

It would be required to coordinate activity between NASA, DOD, and industry, and also provide the ground rules for these communications. More crosstalk should be encouraged especially with the public. The public should be more informed about the technological spin offs from a mechanical technologies program

As a leadership agency for civil space, NASA not only has an opportunity of establish a space

mechanisms infrastructure, but has been remiss in ignoring this critical element of technology in its program to date. It has been left to each project to fund any mechanisms development required to meet missions objectives. Each project focuses on its immediate needs with not attention paid to future requirements. Limited dissemination of technology occurs, and we reinvent at least a partial "wheel" each time.

All of the above is communication. NASA should hold the data base, establish & maintain the standards and come up with an easy, user-friendly, cheap way to disseminate the information.

Everything should be done to share research information. Attempts should also be made to get as much information out to industry as possible and encourage rapid product development where appropriate.

Licensing of all resulting intellectual property in which the government has an ownership interest should be coordinated by the respective government agencies involved -- that is DOD, NASA, or other agency.

Establishment of a SMTI would lead to a more organized approach.
Should add: "Testing & evaluation of brand name products."

NASA can and should provide technology and data upon which standards can be based. Also, NASA should participate in committees and discussions which bring them about. I don't think, however, that we should become heavily involved with the responsibility for the establishment of these standards. We should spend our time doing the technical research, not writing the paper. An item I would consider adding in the above list is participation in interdisciplinary activities (perhaps with the LaRC CSI program or Robotics programs). The contributions made at the generic level in mechanisms would be tested and find immediate application in those programs. Once proven, applications will follow very soon in programs such as Evolutionary Space Station, where robotics is seen as a saver of astronaut EVA time.

There is a strong need in all the above areas. If we are going to meet our space goals new programs and research must be established.

Coordination of new technology development will stifle it. We need to coordinate the requirements or mechanical needs. Standards should be developed and distributed nationally. Consultation is required to interpret standards. An easily accessible and up-to-date database is the key to success. Testing facilities are of paramount importance and are always the last need addressed. Should add, advocate additional testing facilities to your list. Exchange of information is essential to control cost, schedule, and performance of technology. Lack of crosstalk has resulted in high costs, longer schedules, and inferior products to date. Too often we ignore the synergisms between NASA and the DOD. Frequently we are searching for solutions to similar programs. The biggest fault NASA has is that even though we pride ourselves on our communication, there is very little communication from Center to Center and project to project. In fact, almost every new program is structured and costed on foundation statements such as "We went to Mars in 76 and we know how to do that". While our statements are absolutely true, it is almost always a fact that the second project to the moon or to Mars is NOT the same group that went the first time. In addition, there is almost NO exchange of technical information from the first project to the second. Yet the project costs are always based on building on the previously gained information! It is imperative that we improve our communications and that we really learn from each other.

Two areas should be added:

- 1) A method to educate US industry on the technology developed so it could be applied to non-aerospace products
- 2) We need a good PR group to inform the public if technology applied in 1 above is successful.

My "yes" responses involve increase communication and coordination. This ensures that all needs are addressed and that work that has been done or is being done is not duplicated.

- (1) NASA should provide and maintain a centralized NASA-depository for space mechanisms/tribology information to aid in conceptual and final design of systems for space basing and travel. NASA should also develop promising space mechanisms and Tribology technologies.
- (2) Add an item to survey and catalogue past and ongoing space mechanisms/tribology developments by the U.S. Government, civil and foreign countries.

All of the above are needed to maintain NASA in the role it was established for, that is, maintain this country as the leader in space exploration.

Academic interaction should be added. All would facilitate and expedite technology development and provide a forum for much needed information exchange and knowledge of what is being pursued in the community by individuals engaged in the design of new systems, etc.

My bottom line feeling about this is that we don't need to keep establishing new organizations. Too much money is wasted on overhead (i.e. management). We have a library that has current papers on subjects being researched.

In space applications, often requirements vary widely. standard would probably not apply well to many applications. The experts in the field are the people make the hardware perform. by developing an infrastructure, these people well be able to contact each other to consult and for advice.

I think all the above would be useful and necessary. One of the major areas of concern is the contamination question that limits the use of liquid lubes in space. No approach to convince the service community has been successful to date.

NASA should especially endeavor to coordinate and fund new technology programs in areas that will have a strong impact on exploration missions. These missions will likely have the most stringent and challenging performance requirements. Included in this category are the great observatories planned for the end of the century such as SIRTf, as well as long duration missions on the surface of the moon and Mars. I suggest that NASA put together a Tribology Research Working Group with members drawn from the Human Exploration Office, as well as the space centers and industry to implement some of the activities mentioned in the paragraph above. One of the first activities should be to set goals in view of future planned missions.

Comprehensive tests and a data base would save a lot of duplication of effort. Industry standards would insure that people take advantage of past history. DOD is working on bearing tests for SDI. Need to be plugged into their effort.

There is inherent goodness in most if not all of the above listed areas. NASA should maintain test facilities for their own in house use and expertise but should probably not put itself in the business of providing this capability to the aerospace industry. Consultancy and advisory services (and the development of standards) could perhaps best be accomplished with one or more technical societies.

The team work between government and business in developing standards for industrial production and government's injection of new technological advances into the business sector would enhance the capabilities of both.

OTHER GOVERNMENT AGENCY RESPONSES

A well structured program with maximum cooperation and coordination is required to just maintain the pace in which mechanisms are required for future missions - mechanisms certainly will not be any simpler or less demanding in the future.

Should include DOE National Labs in coordination effort with NASA and DOD. Microelectronics Industry of micro-actuators should be added. Reasons for the infrastructure are: (1) much research underway & "not invented here" causes much duplication. Cross funding & multiple funding difficult to make multiple sponsors happy. A Tech Infrastructure could provide the needed coordination and oversight.

Should add (1) develop new materials that are light, strong and durable, (2) develop science base. Should not due standards, a data base or advisory services

INDUSTRY RESPONSES

NASA should be involved in coordinating new technology GE development but should not do so in isolation of other agencies and institutions. Crosstalk between government customers is extremely important, NASA did this so very effectively in the 60's and early 70's and I would like to see NASA return to this mode of operation

The SEI provides an opportunity for NASA to pull its act together in the area of Mechanical Components and Tribology. NASA has been too long silent and absent as a leader in this area. DOD appears to be more aware of long term space mechanisms needs than NASA. Coordination with DOD is essential especially with current budget constraints.

Essential to develop and maintain a "know-how" base.

Not only could NASA "standardize" the industry somewhat, it could provide coordination of gov't Sponsored R&D to meet critical performance issues. Between all our gov't customers, there seems to be absolutely no crosstalk in the mechanisms area.

We need greater coordination, direction, prioritizing. Old centralization, transfer of information, and some place where everybody knows where the information is stored.

Private industry will provide testing facilities commensurate with the need. DOD & NASA research funding & coordination should be separate (competition fosters progress). NASA & DOD tend to have "favorites" at various times to the exclusion of other competent and often less expensive

contractors - varies from decade to decade, depending on who's running the show. NASA & DOD should not be in competition with private industry - They should be planning and regulatory agencies.

The Main benefit of such an effort would be to make NASA available the major portion of an existing knowledge or data base in these areas from one source. Obviously this would not only reduce a lot of engineering time in searching for data but would also help identify any needs for additional technology research deficiencies in these areas.

There is a lot of information in existence, which should be assembled and made available. There is also a lot of additional data needed. But, there needs to be some coordination to be sure the \$ are spent developing useful new data and not on funding pet programs under the guise of helping projects such as the Space Station.

An infrastructure would provide a need service, but I do not see the need for additional standards at this time.

A concentrated effort is needed to achieve economically the goals of the space station, the return to the moon and a manned mission to Mars.

A focused infrastructure would reduce duplication of efforts and accelerate new coating development.

Much of the data acquired in the long duration testing program would be beneficial to the industry. There are presently many unknowns such as bearing cage instability characteristics that could be properly researched to provide design guidelines for precluding cage instability. More work is needed in gear driven high torque mechanisms as gear wear is a major impediment to achieving long life mechanisms.

The ESA Tribology Lab performs similar function already for coordinated effort for European Programs. A centralized organization may provide better support and facilitate technology transfer.

A central clearing house would be helpful for collecting and distributing information about who is doing what and where. This should include data-base capability but not an attempt at standardization. I believe adequate testing facilities exist or will be developed as the need arises and don't believe they should be centralized. The transfer of technology and information exchange would occur as a result of having a central clearing house. This would be an important adjunct to organizations such as ASME, SAE and the annual Aerospace Mechanisms Symposium. A real difficulty will arise in making such a service useful to and known by the design community. Perhaps participation could be made a contractual requirement by NASA and DOD.

The technology transfer program and the capability for literature searches already exists. I think the infrastructure partially exists and has for over two decades; it is the once-a-year Aerospace Mechanisms Symposium. In a limited way it is the vehicle for providing support for the majority of topics listed for many of us in mechanism design.

I would agree all the mentioned areas are necessary.

Numbers 3 to 8 are good. We can do number 1 using the "Aerospace Mechanisms Symposium".

We have too many standards now.

I agree there is a need to establish a Space Mechanisms technology infrastructure by the government. I am not sure if NASA or another government organization, such as the DOD, should establish this infrastructure. I would not delete any item from this list. However, I recommend adding several thoughts: (1) the Space Mechanisms Technology Program should take a leading role in developing analytical tools for mechanisms designs. (2) The program would also take a leading role in the simplification of mechanisms development documentation and process control. (3) I would like to emphasize the need for such a program to develop an efficient communications system with all government customers and ensure the right people have access to the information with minimum "red tape."

Initiate and monitor a program to develop needed space mechanism lubrication systems

Rather than create additional infrastructure, NASA should both increase the prestige and frequency of the existing mechanism conferences, possibly by adding a "futures" section based upon "standard" specs issued by NASA. Best solutions could be presented and then funded for development and test.

There definitely should be a central unit that coordinates the development of new technology, develops a data base that can be accessed by smaller contractors. The major effort in this area of data collection and distribution should be directed at the smaller contractor or researcher.

NASA's objective should be to encourage private sector involvement in space efforts. Its greatest contribution would be to encourage the formation of consortia among private industries.

Industry probably for the next twenty years will have little interest in space programs. Initial development effort has to be accomplished by the government.

Establish a repository of knowledge of from all industries for transfer of industry's technology to space. Publicize the Aerospace mechanisms Symposium, it used to be international - why not now? Include human factors - relating to telepresence.

Avoid costly re-design of components and for systems. GE Ensure engineers have feedback to NASA/DOD specs. Develop a manual or guide for engineers to refer to, to add in the design of gears, bearings, release devices, materials, motors, lubrication, etc.

Providing consultancy and advisory services and facilitating technology transfer would dilute the effort. Other organizations can provide these services. New standards and maintaining a data base are the key efforts.

The following additional task is recommended for the space mechanisms technology infrastructure: "Maintain lessons learned, failure analysis data base manual to prevent potential problems from recurring prior to prototype testing.

Standards for U.S. Industry use should be developed only if they are co-ordinated with the DOD. As a first cut, DOD-STD-83577 (Assemblies, Moving Mechanical, For Space Vehicles, General

Specification For) gives a starting point. However, documents such as this can drive the design in ways that aren't always desirable, so they should be developed with some caution and applied intelligently.

NASA should fund "low temperature materials--mechanical, electronic and thermophysical properties information analysis center (Like HTMIAC at Purdue University)

NASA should not maintain adequate testing facilities for U.S. space interests, since this is an industry function. Government is not in the business to compete with industry. If it is sub-contract then ok!

Like all infrastructures, the success will be dictated by political freedom, capable staffing, adequate funding and the courage to be at the forefront. NASA, if they are bold, can be an effective leader since they have the experience and courage for directing such a center. They should be as formidable and disciplined as their predecessor NACA. They set the standards.

NASA would be a good initiator/caretaker/clearinghouse for such technology because of the many sub-technologies (Laser Hardening, diamond coatings, solid lubricants, surface chemistry, electron microscopy, etc.) that must be brought to bear and synchronized to successfully attack the above problems. Additional areas needed to be covered are: Initiate "seed" and encourage industrial research.

Because of the long history of tribology research, and the well-established first-rate facilities, NASA, especially the LeRC, is in a unique position to assume the leadership role to coordinate this program.

Provide for Co-operative efforts between US (NASA) and Canadian (ESA) programs in mechanisms/tribology.

A coordinated effort, in principle, would be very beneficial. The practical implementation of such a system would work only if communication within the system was easy & bureaucratic requirements were minimized.

I would like to see NASA become a main tribological center for U.S. industries.

Forecasting of industrial applications as follow up of space tech's. This can be used to involve even the private Co's in risky projects.

The role that NASA plays should be well focused and not disrupt the long established working relationships between the NASA Field Centers, DoD organizations and the industrial contractors. Coordination is therefore required to minimize duplication of efforts (\$ savings), maintain a reasonable technical database so that previous technology work is not unnecessarily or unknowingly repeated (\$ savings) and NASA field centers with particular expertise (like LeRC in tribology) can work on problems that fit their technical strengths (\$ savings). The writer believes that dollars could be wasted in trying to develop large test facilities that are available elsewhere, but cataloging those available (DoD Moving Mechanical Assembly Spec (MIL-A-83577B), Test Requirements (MIL-1540A), JSC-31000, etc. are adequate. Update and revision may be appropriate however. Cataloging and publishing appropriate standards, mechanism design database and design analysis tools would also be useful.

A possible role model for NASA in the area of space mechanisms would be the European Space Tribology Laboratory (ESTL). ESTL serves as the repository of mechanism and tribology technology for the European Space community. They publish relevant technical reports frequently, assist industry in specialized problems, provide funding for sponsored industry mechanisms activities and host yearly mechanism symposia. More importantly, the people of ESTL have a quality track record performing and reporting on meaningful mechanism work.

NASA should be more concerned with the general overview of the various programs and provide support by creating standards and test facilities accessible and applicable to a wide range of companies and disciplines.

Depends, most companies have test facilities but additional test areas for live/service development-type tests could help

A new set of standards is not necessary - NASA should encourage development of existing standards.

Relying on DOD may cause problems for NASA should DOD funding or missions disappear. Coordination is necessary but NASA should posture itself to do the job alone should DOD pull funding.

Communication & a conduit of information is needed. Turn the aerospace mechanisms symposium into an organization with dues, a journal, etc.

SSF and future space missions will require significant design and development of long life, low maintenance mechanical components by a wide variety of designers geographically located across the U.S. If a standardized data base on space mechanisms existed, significant savings could be realized during DDT&E and a more uniform class of mechanical components could be developed.

Efficient and effective management is definitely required to meet those goals.

It has been my experience that every company does its own research quite frequently duplicating the effort of other companies. Common research and data basing could eliminate this and reduce overall costs.

I'm not stating that NASA and DOD research should be "coordinated" but rather that their individual components should exchange ideas and expertise.

Standardized elements (highly integrated chips, motors, seals, sensors etc.) have too large a development cost to burden any single program. I'm sure the best approach is for government to fund development of these facilitating technologies that could then be applied to space mechanisms on an application to application basis.

For the same reasons as stated in #1-3, plus:

- 1) NASA and industry should be jointly responsible for the development of industry standards - ensure the standards are thorough but viable.
- 2) NASA can collect information from its government customers and provide it to others through exchange meetings, databases, etc. Market competition discourages direct communications between contractors.

As an example, the tribology research efforts in this country today are an uncoordinated collage of divergent efforts, duplication and conflicting goals. Funding and management are from virtually every branch of government including NASA, the Air Force, National Science Foundation, DOE, and others. No effective steering committee or guiding body is coordinating and insuring the effective utilization of resources.

The old timers have left or are retiring rapidly. It has become evident to me that the new engineers are not aware of the pit falls. Materials and lubrication questions come up regularly. The industry needs guidelines based on a variety of operating parameters.

Establish a baseline of technology needed for the new space missions.
Standards development should include the use of SI Standards with the objective being total conversion to the SI System.

One of the biggest benefits to the American public of the Space Program has been the spin-off technologies being applied by American businesses to maintain America as the leader in high-tech equipment.

Probably a good idea - is this bordering on too much "participative" research & technology? NASA needs to evaluate its own managerial philosophies and structure before attempting to establish a new agency entity. The terminology infrastructure implies adequate compatibility/communication and requires streamlining to guarantee efficiency in task accomplishment. Referring back to the answer to question 2, implementation of new technologies is often better accomplished within an entirely new generation of product (ie vehicle/design). Perhaps a restructuring of NASA to whatever degree necessary would better facilitate the establishment of a Mechanisms Technology infrastructure. The tasks outlined in question 4 are obvious duties/responsibilities of such an agency entity yet there is doubt that NASA could efficiently accomplish such an endeavor utilizing its outdated managerial/structuring technologies.

Suggested Additions:

1. Define requirements for specific mechanisms
2. Develop solutions
3. Test solutions

QUESTION (5): What kind of space qualification techniques need development?

NASA CENTER RESPONSES

- Qualification of criteria to be used for accelerated testing of wearing and lubricated surfaces such as gears and bearings. It is difficult to verify the adequacy of accelerated testing. In addition, it would be useful to have a uniform basis for comparison of test results.
- On orbit shuttle test bed ("gas can like" facility) with the fundamentals provided and limited prep work required of the user.
- Life test and property characterization facilities for mechanical systems and electronics including vacuum, thermal, contamination and radiation environments. This may also require some field tests such as high desert testing for dry, high and low temperature, high contamination environments.

Dither motion over small degrees of rotation. Investigating best material selection. Some sort of stick slip test for the removal of the joints on "Freedom" after 15 years of exposure to? Sliding mechanism surfaces - How are they affected? What effect will Astomag have on rotating mechanisms over the long haul?

In the case of bearings, these are no life tests currently being done which would run different bearings at different loads at different RPM's with different lubricants at various temperatures in vacuum. As you can see the permutations are endless and this could be a large, expensive program covering years of testing the bearings. No individual projects does this, so a "Space Mechanisms Technology Center" would be required to do this necessary testing.

Evaluation of bearing & bearing lubrication. Mechanical component standards, gears, ball screws, gearboxes.

Wear of Components.

NBS type of testing could be done to develop and verify standards for accelerated life testing.

Accelerated testing for lifetimes of 30 years poses an extremely difficult problem. Even when only 5-10 years are involved, one never really knows whether the speeding up of the test cycles affected the result, either positively or negatively. Basically, some long, 10-year tests are needed - probably at the real-time rate. Then we'll need an ability to extrapolate to 20 or 30 years.

Zero 'G' systems

Requirements for use in the Lunar & Mars environments have to be established first - then appropriate qual techniques can be defined.

Materials, lubrication, g-negation systems

I don't necessarily believe that better testing methods and facilities is the answer, at least not yet. First you have to have the availability of testing facilities. We need more facilities in which to test our spacecrafts. Once we have enough the time required to get a spacecraft tested will be reduced simply because the waiting period is shorter. Then we can begin improving the

qualification/testing techniques and facilities.

The whole area of space environmental testing needs NASA-development. Fundamental research needs to be done to allow accelerated thermal cycle life testing to be performed. Computer simulation and modeling need to be exploited and integrated with real time testing to allow reliable predictions of system performance including identification of failure susceptibility, performance degradation, etc.

Thermal vacuum systems, atomic oxygen simulators zero gravity simulators capable of functioning large spacecraft prior to launch.

At this time, the testing methods utilized to qualify space hardware for flight are adequate. However, testing techniques to simulate long term space/zero gravity exposure need development.

Mainly accelerated testing methods. Included should be accelerated thermal-vacuum tests and wear tests in the space or extraterrestrial environment. Development of these test methods to the point where they are credible is a significant technological challenge. This development should include space testing on the Shuttle or Space Station at every opportunity to correlate with ground test hypotheses.

A guiding precept might be that given the proven safety performance in space to date, less not more emphasis can be given to space qualifications for most new uses of existing technology and of many anticipated applications of new technology. As in all human endeavors, time is usually of the essence. There should be no more time expended to retest the wheel than there is in its reinvention.

Materials, EVA capabilities, and lifetimes need development.

I can't think of any real needs that are not covered from the existing engineering data base.

Broader approved materials list, correlation between testing required and actual conditions, coordination between centers as to requirements, better integration of new research and technology.

Having been involved with many space satellites and NASA-hardware I feel qualification standards and guidelines should be established. I have found that different agencies or companies seem to have varied guidelines on qualification standards. Such as cleanliness levels, materials used, and different testing techniques.

Thermal vacuum tests with multiple targeting is required. The tendency toward larger and larger spacecraft is complicating both the integration and testing capabilities. More complex and discriminating ground support mechanisms are required to support testing. Large thermal vacuum facilities are required to provide the testing for fluid and gaseous transfer mechanisms, to verify lifetime leakage prediction for contained systems, and to verify lifetime leakage prediction for contained systems, and to verify sophisticated IR sensor capabilities. The most pressing need in the Agency is to provide support for the Lunar and Mars missions in the area of facilities. There is an appalling lack of large volume clean rooms, smaller clean rooms for instrument and mechanical/electrical subsystem assembly activities, vibration and clean, large thermal vacuum equipment and facilities to adequately test the subsystems and to verify proper functionality. Facilities for dynamic testing or to characterize lubricants are even more scarce.

The best qualification technique for space mechanisms is to test them in the environment they were designed to operate in. For programs such as HEI, components could be installed on commercial free flying platforms, a specially funded LDEF type craft for component testing or THE Space Station. The components could then be duty cycled from the ground or by astronauts in space. Further qualifications could be accomplished by installing instrumented candidate mechanisms on unmanned probes to Mars and other planets and recording their performance.

More rigorous qualification techniques must be developed to ensure that the mechanisms will be free of damage during the launching period so they will perform as expected. Performing tests in different G environments should be essential to ensure that the mechanisms works in the specific gravitational field. If the test facility for simulating the different G is being impossible on the ground, we believe the next best thing to achieve this goal is to simulate the mechanism on a computer.

I don't think it necessarily has to be accelerated but testing must be accomplished. Example -it seems the Hubble should have had more total system testing.

Don't know how you accelerate testing methods. Of course simulations and computer modeling should be used where feasible, however, there is no substitute for life cycle testing under expected operating parameters and environment. This perhaps could be integrated to shorten required testing if data could be correlated to model early by some means.

It seems as if there are a million requirements in just as many documents required to get a test approved for launching on the shuttle. The problem is, the people signing off the test usually don't understand what the requirements really are.

Contamination testing needs clarification and new facilities, especially in the areas of clean vacuum testing. Much testing delay is caused by QA. Perhaps the role of QA needs to be examined-some of the power exercised by QA could perhaps be limited.

Every program is different depending on the requirements imposed. Usually the more sophisticated the organization doing the work is, the harder it is to do a test that satisfies anyone. (1) Managing quality to control cost is the most important. (2) Standardizing modeling approaches to give real time answers is also very important and cost effective. (3) Testing is very application specific and no universal test will satisfy everyone. (4) Broad load spectrum is needed to allow proper choice.

Standards for bearing testing (all parameters-friction, noise, wear, life). Standards for LED life testing (for optical encoders) and understanding of effects of accelerated testing.

I don't know... but whatever we do presently isn't adequate... we still have far too many failures for the amount of money and manpower allotted.

Cryogenic temperature test facilities are lacking. One or two degree Kelvin temperature test chambers will be needed in the future (superfluid helium temperatures)

Long term/low cycle (i.e. very long period) mechanism actuation in environment.

I do not believe that accelerated testing is what is NASA-required. First, I think that analytical

methodology and a data base must be developed. Environmental long term testing under simulated conditions must be undertaken.

Partial "g" when applicable and the Lunar/Mars environment

All of them - really, especially if we are to afford space flight

OTHER GOVERNMENT AGENCY RESPONSES

Since the space craft industry is so conservative that nobody wants to be the first to launch and fly a new design, especially mechanisms, we need new approaches, including accelerated testing techniques. The SDIO program is trying to involve the Prime contractor mechanisms designers and program managers from the beginning with the ideas that if they have a part of the program that in the end they will have the confidence to include the new technology in their designs. We need to apply as much advanced knowledge in materials, design, computer modeling, accelerated testing, etc. in a truly interdisciplinary team effort to compliment each effort in a well coordinated program.

Design for telerobot maintenance. Nuclear industry (ie DOE Nat'l Labs) have spent many years (40+) and millions of \$ developing equip for remote handling. Many facilities experienced huge delays & some shut down due to inadequate development of telerobot remote handling. Future space missions will need telerobots to reduce costs & EVA potential hazards. Equipment must be qualified for telerobotic assembly and Maintenance.

Simulated zero G testing of deployables, gimbals & other components hard to test in 1 G. Radiation effects, atomic oxygen on lubricating systems.

Lubricant/materials testing under cryogenic conditions, dust abrasion, high temperature lubrication, corrosion, corrosive wear, and materials durability.

INDUSTRY RESPONSES

Some of the needed testing techniques which come to mind are: 1. Fatigue of components stressed repeatedly for long periods of time, 2. Chemical effects of the space environments, e.g., radiation on lubricants and other components, 3. Long term stability of lubricants and chemicals, 4. lubricant loss through creep and evaporation, 5. incubation periods for catastrophic wear, e.g., subsurface stress of components which cannot be detected until it is too late, and 6. extremes in temperature and pressure. The important thing is that the accelerated testing method does not change the mechanism of degradation and also does not perturb another characteristic of the component being tested.

Precision rolling/sliding contact test capability in controlled environmental conditions. Methodology for "tribological" accelerated testing rather than "mechanically" accelerated testing.

Qualification techniques are needed for determining life of lubricants, life of materials, and the effect of exposure to a space environment. Other areas are compatibility of materials, life mechanisms, and advanced modelling of space mechanisms.

Bearings for propulsion systems, seals for propulsion systems.

1. Material characteristic changes in space. 2. Research into durability testing.

From my standpoint, none. Mechanisms of adhesive and abrasive wear are reasonably well understood. The usual shortcoming in accelerated testing is failure to take the time/money to adequately model and instrument the test before actually starting. Factors of 30x or more are realistically achievable with either fluid or dry film testing.

1. Valid techniques (or at least widely accepted techniques) for fluid lubricant accelerated testing. 2. Atomic oxygen testing techniques, facilities. 3. LDEF results: NASA/DOD should fund investigations, not leave it to the funds, inclination, priorities of the individual companies. This program was intended to accomplish much of what we will have to do again. Don't waste the LDEF effort.

Long life testing for seals and electronics.

Effect of long-term space exposure on lubes and wear/bearing materials. How to get reliable evaporation rates, creep rates (in case of lubes), and other deterioration rates?

Accelerated testing of lubricant life and wear surfaces.

Effect of contaminants on friction and wear.

My experience with mechanisms testing leads me to the general conclusion that accelerated testing is inappropriate for long duration mechanisms because operating these devices at higher speeds changes the operating characteristics sufficiently to invalidate the test. Higher speeds brings changes to lubrication film thickness, changes temperatures of component parts, affects lubricant flows through the mechanism, etc., and results in invalid test conclusions. What is needed is dedicated (small) chambers running for real time periods.

Accelerated life testing of lubricants, material outgassing, particulate generation, radiation effects on material properties is needed. Also needed is realistic vibration and acoustic loading spectra.

Accelerated life test in simulated space environment (vacuum, O-g, radiation, temperature) is needed.

Long term cold/hot temperature soaking between periods of mechanism activity -accelerated testing cannot fully assess long term inactivity periods.

I don't know of any to add.

None that I know of.

The following space qualification techniques need to be developed: (1) Zero-gravity simulation for the qualification of ejection mechanisms, vibration/ isolation pointing devices, robotic manipulator arms, solar array deployment, etc. (2) Cost effective techniques to determine life cycle mechanism performance without degrading the flight mechanism.

This question first requires a categorization of the factors limiting a mechanism's life; e.g., is it

number of cycles, operating environment, lubrication capacity, etc.? Once determined, it can then be decided whether accelerated test means can be devised.

It is difficult to impossible to do accelerated testing on fluid lubricants. Therefore we should concentrate on doing accelerated testing of dry lubrication systems, where there would be a large payoff for long life requirements.

Commitment with funding to conduct realistic life testing. use accelerated testing for comparison purposes only. Little evidence is available that accelerated testing is understood. Need equipment to do one set of testing, i.e., thermal/vacuum, vibration, thermal/cycle.

Space chambers with the ability to expose the mechanism to particle bombardment, i.e. micro-meteorite, etc.

Testing for most aspects of the space and launch environment are pretty well in hand with the exception of radiation (in any orbit) and the atomic oxygen environment of near-earth orbits.

Flight assembly and maintenance demonstrations and long duration functional and materials tests.

Micro-g environment testing.

Solar Array Deployment testing in Zero-g - full up testing of large arrays may require dedicated facility.

It has been my experience that all high reliability and maintained hardware follow a Markov Chain failure distribution. There has to be a distinct difference in testing-for-confidence of maintained vs. non-maintained components and systems. Further there needs to be a major analytical effort to evaluate statistical confidence of the reliability of an operational system achieved by testing as opposed to obtaining the same confidence by testing the system components. We must study the value of deterministic vs. statistical models. I favor use of deterministic models to develop an understanding of the assurance techniques used to design a part which will not fail: use of safety factors, safe life and fail-safe.

We currently don't do any qualification testing of mechanisms which subjects them to specific space environments which could be damaging, i.e., atomic oxygen, ultra-violet degradation, micro-meteorite bombardment, etc. These space unique environments should be mimicked in qualification test programs.

Correlations between actual flight and earth environment acceptance testing would be invaluable, especially for liquid and solid lubricant predictive performance. Since this is not always feasible, accelerated testing assumes a critical role. For certain lubrication regimes, accelerated testing may not provide useful information, thus predictive analytical model development is needed. Correlations between laboratory level testing with component behavior also would enable rapid screening of advanced tribomaterials, surface modification techniques, and lubrication methods and result in faster technology transfer.

One of the major problems is how to accelerate test. Any program that works can add information. But there is great value in starting long term tests and in collecting long term information on promising lubrication systems.

Accelerated life tests need to be developed.

Coefficients of friction of various solid film coatings for tribological applications (Also, radiation resistance and outgassing.) at low temperatures (20° K) and low pressures (10^{-8} to 10^{-11}).

Life testing techniques and guidelines.

Perhaps a first step is to approach industry and request their volunteering all their results for life testing, wear characteristics of lubrication and materials. This could be the basis of a library from which standards can be established and proceed to further extensive test programs.

Need to develop "micro analytical" wear and friction analysis models so that proper "scaling" techniques, dimensionless groups, etc. can be defined which address both the thermal and mechanical aspects of rubbing wear in a vacuum. Right now, how you might scale velocity, load, rubbing time and bulk temperature, etc. to get the same surface phenomena occurring at the interface in the test versus actual situation (let alone the rate at which these phenomena deteriorate the surfaces), is poorly understood. Without adequate models of this sort, the only reliable tests will require operating the actual component in a vacuum at cryogenic temperatures. These tests are complicated and expensive.

There are two aspects: (1) Hardware Facilities. I envisage the need of building larger-scale (larger than the vacuum-chamber friction/wear testers presently available at LeRC) facilities that can simulate the space environment and can be used for long duration tests. (2) Analyses. Proper performance and life parameters need be brought out to guide experiments and to correlate test results.

Adequate simulation testing of (1) Mechanism Components, (2) model tribo-contacts in vacuo, along with other environmental factors, e.g. atomic O, radiation, etc.

Long term life testing and space environmental effects of lubricants

Deterioration of lubricants in the space environment. UV exposure versus strength properties of non-metallic mechanisms.

For our company ready access to thermally cycled vacuum chambers would make a big difference in development. We are a small company and developing space mechanisms is very costly.

An alternate method of addressing requirements for hard vacuum such as testing in dry nitrogen atmosphere would allow cheaper and therefore more testing of space mechanisms.

Techniques for efficient and reliable identification of the mechanisms of wear. Establishing the reliable criteria of accelerated testing of friction and wear.

I see no particular need for anything new in this arena.

The validity of accelerated life testing, particularly for liquid lubricated components, is nearly always in dispute. Accelerating the speed or increasing the load of lubricate contacts can significantly

change the failure mode. Scale factors between accelerated life tests and anticipated space service are ill defined. This question is not just one of academic curiosity, since "big bucks" are spent in thermo-vacuum mechanism life tests. Based on the writer's first hand experience with the space station's solar alpha rotary joint, proving 30 years of mechanism reliability in a schedule allowable period of about 6 months is anything but easy.

Actual flight testing of prototype designs.

Zero-load simulators (suspend moving loads to simulate zero-g)

The following need to be worked on:

- Life testing - zero 'g' tribology
- Large structures characterization
- Deployable structures verification

Certainly accelerated life testing will be useful in screening technologies but actual simulated environment will be needed to qualify systems.

Not qualified to say

Areas which need research:

- 1) fracture control
- 2) thermal analysis
- 3) structural analysis

Lubricant coatings, films, oils, greases need further definition for acceptable space qualification techniques.

Long duration space exposure

Not qualified to answer

This is not my area of expertise. No comment.

Accelerated long life (30 year) test techniques.

- 1) Accelerated testing of course
- 2) Large scale systems testing - large chambers
- 3) complete full scale tests for the smaller satellites

- 1) Accelerated life testing of integrated systems in a simulated environment

(a) Coordinated exchange would decrease the number of redundant development products, increase the maturity (on down load time) rate of new systems, and would identify those technologies that need extra attention in order to meet the planned mission goals and timelines.

(b) Reduce design/development time due to having an established database of mechanisms technologies to build from and by avoiding the "lessons learned" by others.)

- 2) Functionality testing with a loss of redundancy

- 3) Environmental testing that includes thermal cycling, radiation exposure, debris impact, plume

impingement etc.

An expansion of thermal/vacuum capabilities is very much needed as well as weightless environment testing. Also space environmental factors need to be addressed. Too many times large space mechanism must be verified for the first time in space (i.e. shuttle payload bay doors/Hubble solar arrays)

First, a review and evaluation of previous methodologies for accelerated testing should be conducted to determine the merits of previous efforts and applicability to future work. Also, too much testing has been done with no theoretical analysis to determine the validity of methods and effectiveness in correlating to real time performance.

1. Long-term testing on earth under simulated space environments.
2. Actual testing of mechanisms in space; lots of testing

Accelerated testing in advanced technology areas is not feasible. This was investigated thoroughly in the Apollo Program. All of the experts in a wide variety of industries agreed that one depends on usage data after "X" time of use to compare to previously forecast results before one can then forecast results on the next set of accelerated life tests. But, it can only be done in extremely common areas - not like what we need for space technology.

Test facilities using computer modeling and physical testing labs need to be built. The short fall in computer resources to interface with known data collected on various missions is critical. The future of quality testing should be phased through computer modeling and afterwards physical testing performed for comparative data. The use of existing data for modeling situations should produce new process concepts that would lead to faster incorporation into the program.

To qualify an entity for space application requires an evaluation of the entities performance when subjected to specific space parameters normally qualified by duration. Technologies associated with evaluation of entity performance prefer to implement accelerated testing techniques (ATT's). These techniques are normally science specific, ie, metallurgical ATT's are methods of obtaining desired QC (quality control) evaluations in minimum periods of time without sacrificing simulation and evaluation parameters. The kind of space qualification parameters necessary to evaluate would be better defined by those analyzing the Long Duration Exposure Facility (LDEF).

Solid lube can be accelerated by increasing travel. Liquid lube acceleration can be approximated only by increasing temperature, load or speed. It is best to avoid one-shot systems completely for long life & high reliability, i.e. add oil supply systems.

QUESTION (6): What are some specific current or anticipate Space Mechanisms needs?

NASA CENTER RESPONSES

List of potential equipment requiring mechanism development (list intentionally limited to items probably not easily maintained in a shirtsleeve environment.

Fixed Scientific Equipment:

(1) Large Telescopes- Gimbals and motors; smaller actuators for smaller mirrors. (2) Observatory domes, windows and ports. (3) Facility helium and nitrogen liquefiers and liquid handling systems. (4) Mechanical refrigerators for site cooling.

Habitat, Construction, Drilling and Maintenance and Heavy Transport:

(1) Drilling and coring for heat pumps, water, etc. (2) Heavy excavation equipment for raw material excavation and handling. (3) Pumps for heating and cooling equipment (must preclude refrigerants leaking into breathing spaces). (4) Airlocks and vacuum pumps. (5) Antenna Pointing. (6) Waste and vent valving. (7) Heavy and bulky material transport systems. (8) Power generation and storage (motor/generators for high voltage AC power, pumps and compressors for electrolyzed H₂ and O₂ storage). (9) Antennae and sensitive structure deployment and furling. (10) Inflatable structures for temporary and semipermanent shelter (for both men and equipment). (11) Fully telerobotic servicing and assembly for dangerous environments such as long duration exposure during solar storms, long trips on the lunar and Martian surface not feasible with the overhead of life support systems. (12) Heavy transport for construction and movement of major equipment. (13) Lunar to orbit launch facilities such as an electromagnetic rail gun.

Exploration and Mobile Science

(1) Light weight rover (all terrain, man-rated). (2) Long range, light weight rover (non-man-rated, telerobotic with gripping). (3) Portable drilling and coring. (4) Umbilical connects/disconnects for refueling and connecting vehicles.

Critical Technologies

(1) Seals and sealants (O-rings, gaskets, suit and tent materials). (2) Bearings (lubrication, contamination sealing). (3) Motors and geartrains (lubricants, contamination sealing). (4) Magnetic or other non-contacting bearings for sealable long lifetime equipment. (5) Abrasion, radiation darkening and contamination resistant optical surfaces for sensors, viewports and solar cells. (6) Further development in composite materials for both mechanisms and structures. (7) Need further development in lightweight, high strength alloys such as advanced aluminum alloys (i.e. Al-Li). (8) Robotic servicing and unmanned exploration augmentation, particularly fully telerobotic operation. (9) Bio-mechanisms- human life support facilities will require especially high degrees of reliability, serviceability and diagnostic capability. (10) Wide speed range direct drive systems minimizing the use of gears. (11) Power generation. The key to many technologies is the availability of power. This may be met with ruggedized, light weight, efficient solar cells and the technology to produce them on the moon, selconothermal generation, surface/subsoil thermopiles, light/dark zone thermopiles or nuclear power. How much power will be available and when it will be available during the exploration and habitation may be both technology selecting and rate determining. Any or all of these activities are likely to require mechanisms development.

- Robotics
- Construction, assembly & servicing
- Instrument telescope mounts, pointing systems. gimbals
- Mobility devices (on planet/moon surfaces)

1. Magnetic bearings, 2. cryogenic lubricants, 3 lubricants for high hertzian stress sliding contact problems, 4. improved battery technology.

In general, the contractors we deal with are hesitant to reveal the best solution to a problem because it was developed for another customer. That customer may be DOD. The advancement of technology and enhancement of our scientific awareness is being hampered by \$ and politics.

Several are anticipated for the Flight Telerobotic NASA Servicer (and objects it will work on): (1) Numerous robotic joints, grippers and other robotic tools and tool changers, (2) latching mechanisms to hold and release payloads and (3) mechanisms for making and breaking utility connections. Also these connectors must be robot friendly.

I don't think the future designs need to be completely new, just longer lasting materials and lubrication systems are needed.

Servomotors, Payload ejection systems for STS, and vacuum tight, reclosable telescope covers are needed.

The WP-3 Prime Contractor (GE ASTRO) is developing the following mechanisms: (1) APAE(attached payload accommodation equipment) Payload Attachment System, ORU's, Utility Connect-Disconnect Device, Mechanical connect-disconnect device. (2) EOS/POP (Polar Orbiting Platform) ORU's, Inter-Module Connector (for possible ELV servicing docking), Solar array and High Gain Antenna deployments.

See 1c again. (Lubrication of reaction wheel bearings is a probable area of difficulty in reaching 30+ years of orbital life, but I don't think one can definitively say that current designs are not adequate. i.e. longer life oil reservoirs could solve this problem.) On the GRO mission we have had to add bearing heaters to our Reaction Wheel Assembly (RWA) bearings to keep the temperature over 45°F. Otherwise, the oils used become too viscous and the large (52100 CEVM) bearings begin to scream (means damaged rolling surfaces). The use of space craft electrical power for this purpose is undesirable from a systems standpoint. Increase protection and insulation of the bearing areas of RWA's are needed.

True zero "Gee" zero tip off, signal sqibb separation

Adequate low speed rolling element bearings for vacuum use. (Speeds lower than that for elasto-hydrodynamic lubrication)

(a) Guidelines on the minimum and type of testing for qualification of long duration space mechanisms.

(b) Comprehensive data base on flown lubricates their application, and results

(1) New Talent: Young engineers who typically have the most innovative ideas.

(2) New Materials

Already mentioned are the Space Station which includes a multiplicity of needs, eg. the development of an improved MSC/MRMS, Automated construction devices for space construction, and long-term operational mechanisms such as an improved alpha-joint when the need for replacement arises : extraterrestrial applications (lunar and Mars bases) where the problem of dust contamination must be solved and the applications include light-weight cranes and rovers; and the

Mission to Planet Earth for which a 30 year life is contemplated. Military needs include rapid articulation and long life control devices for rapid slewing. Outgassing of lubricants will be a major issue in these applications.

I am currently at Kennedy Space Center for the LDEF NASA-satellite retrieval. I feel much has been learned from this effort concerning materials, torques, radiation, meteorite effects. This information should be available for all and if everyone learns together much more could be learned by all.

The general area of telerobotic and autonomous robotic mechanisms.

Translational mechanisms for both crew and equipment. (C.E.T.A.) Robotic manipulators, both human and computer controlled. Sealed joints for the transferring of materials between operative stations or vehicles. Safety restraints to secure crew or equipment in the prevention of accidents.

All mechanisms are unique for space instruments.

Specific areas in need of development include: Tribology, Bearings, reliable and self-verifying deployable systems, cryogenic coolers, ultra-stable material and structural systems for optical instruments, precision pointing and control mechanisms, vibration isolation systems, robotically constructed very large space structures.

I just finished a flight experiment. We could have used information on latches, bearings, lubrication, materials, EVA interfaces. All of this info is out there somewhere. Its just hard to find. What we need is a bulletin board that I can access from my PC and pull up specs. Drawings and pictures. NASA needs to improve its communications and requirement exchanges between the centers.

Heavily loaded truss joints for constructing aerobrake support structures and for attaching spacecraft components to the Aerobrake. Heavily loaded "line" joints for constructing tanks, habitats, and for aerobrakes. Articulating joints for advanced spacecraft concepts.

Advanced, intelligent and self-propelled robots capable of travel and performing programmed work and tests on space structures and celestial bodies such as claimed in US Patent 4,738,583 (copy attached).

Any project that will fly in space will have use of space mechanisms. Most will be based on previous designs.

Development of long life (5-10 years), vibration free ($<0.1\text{N}$), cryogenic coolers (30 K, 40K and 55K each with 2 or more watts heat lift) is required. Accurate, light-weight low temperature ($<55\text{ K}$) thermal switches are needed. Development of technologies to make and test advanced IR sensors with new materials capable of operation in the very long range IR is required. Laser technologies are in dire need of having their efficiencies improved as well as how to accommodate the power and thermal problems encountered. Most laser systems are too heavy for practical space flight and require far too much power. Highly accurate spacecraft pointing systems are needed, inexpensive and affordable pointing systems for instruments are needed. High volume data storage and data transfer mechanisms are required (300 megabyte to 500 megabyte recording and playback, random access) to name just a few. Some other space mechanisms

needs are an adequately functioning very large (4 ft to 20 ft diameter) rotating joint which can safely transfer fluids and gases simultaneously without leaking or losing efficiency, thermal subsystems which can be self adjusting that will cover and range from very close to the sun all the way out to and beyond Mars and provide a livable environment for astronauts, improved docking mechanisms, telerobotic mechanisms for maintenance and repair activities for long term missions, improved astronaut personal propulsion systems accompanied by a compact guidance/orientation system, and improved space suits with increased mobility, better thermal control and more flexibility.

- Latches to attach items to space station
- Manual & remotely operated valves
- Tubing or piping joints

Some areas of work that stood out at the recent symposium:

- high repeatability in robotic components
- reliable and versatile docking mechanisms
- operation of mechanisms in vacuum and/or over long life
- the ability of mechanisms to withstand the high-g condition of lift off.

(1) Valves, disconnects, regulators capable of operating continuously or intermittently for more than five years without failure and requiring no maintenance or lubrication. (2) Actuators for valves and mechanical components that can be operated electrically as well as manually by an astronaut and/or end effector. (3) A quick leak repair kit for fluid transfer lines. (4) A manually driven electrical power supply capable of recharging portable electrical power tool and appliance battery packs. (5) Manually driven mechanic power/transmission device. (6) Jam proof latches, actuators, gears fasteners designs requiring no maintenance or lubrication. (7) structural shell leakage repair devices.

Interconnects between space station and free flyers for replenish must of propellants, propellant transfer systems inspection and repair of meteorite shields, etc. Design for minimum maintenance and easily repaired systems, quick disconnect modular concepts using standard interfaces and components and tools.

Efficient transfer of mechanical power through an environmental interface. Development of metal matrix composites. Electric motors for long term vacuum operation.

Lightweight, non-contaminating, safe, long life actuators need to be developed to replace pyrotechnics: ie.: (2) wax pellets need to develop increased life and overheated wax control, (2) shape memory alloys need to be developed as actuators in space.

Passive and active dampers.

Standard approach for dry lube of anti-friction bearings. Approach that will always work for lubrication reservoir in bearing retainers. Specific numbers for varying loads on plain bearings at high vacuum and different temperatures.

"NASA Standard" scan actuators (for high and low precision applications). Long life bearing designs for particular applications (gyros, reaction wheels, precision gimbals). Dry bearing coatings for cryogenic/outgassing-sensitive applications. Long-lived optical encoders. Class S R-

to-D converter, low-power inductosyn. Low-power, space-qualified magnetic suspension/magnetic bearings.

- A modular-standard electromechanical payload interface that provides a means for astronaut EVA or telerobotic servicing.

- More dexterous (and intelligent) robot manipulators and end effectors

- 1) Fluid transfer mechanisms

- 2) Robots

Cyromechanisms down to 4 degrees K.

Predicable (linear?) Mechanism response. Self-lubrication/dry lubrication, i.e. no/low outgassing.

Space station mechanisms, robotics, long term operation bearings, traction drives, lubrication, both liquid and solid, remote operated vehicles, such as land rovers.

- Mechanisms to control Nuclear reactor in Lunar/Mars environment

- Power systems Mechanisms in general

Robots, articulated rocket nozzles, aerobrakes; operations robotics bays in transportation systems/nodes in space and on planetary surfaces - and the list goes on.

OTHER GOVERNMENT AGENCY RESPONSES

Precision Pointing and tracking Gimbals, Control Moment Gyros, Reaction Wheels, Momentum Wheels, Solar Array Drives, Cryocoolers, Pumps for Thermal Management of Fluids, Homopolar Generators.

High precision, long life gimbals.

The following things are needed: long lasting lubricants, new tribomaterials, new design guidelines, sealed for life moving parts, self-lubricating composites.

INDUSTRY RESPONSES

Bearings, Cams, Hinges, Sliding Electrical Contacts, and in general, the need to conserve space and weight.

Tribological systems for rolling/sliding contacts lubricated with minimal (or no) lubricant supply over a large temperature range, Turbopump bearing technology for heavy launch vehicles.

The tools at all centers should be compatible. For example MSFC and ARC use two different version of NASTRAN for analysis of various SLS payloads, this incompatibility costs a great deal of time and money trying to convert back and forth.

Traction Drive Mechanisms, rolling element bearings for long life, turbo-pump bearing design, fundamental understanding of transfer film mechanisms in LOX environment, dry friction bearings.

Bearings for solar panels

Precision Pointing mechanisms (accuracy and life), Active damping (better jitter control, stiffness control), vibration isolation (prevention of crosstalk), better material usage (strength, weight, etc), better dry lubes, motor magnet energy product improvements, better hard coatings.

1. Ground-based testing techniques that simulates space environments.
2. Logical approach to study of latching/delatching processes.

Prime need is power and signal transfer devices.

Valid techniques for fluid lubricant accelerated testing. Atomic Oxygen Testing techniques and facilities.

Fluid couplings (QD's) with 30 yr life. Electric DC motors that do not require brushes or complicated electronics. Magnetic docking mechanisms.

Long life, reliable bearings, seals, gears, cams, etc., as needed by the overall design.

The primary need is to develop and test bearing/lubricant systems to extend life for long duration missions.

Coatings for foil bearings to be used in high speed turbo or electrical machines.

Better understanding of cage instabilities & how to prevent instability, better understanding of gear wear in high torque applications, design studies of high torque motors which do not utilize bearings (gear wear is usually the weak link in the mechanisms), better understanding of how to maintain hydrodynamic film thicknesses in mechanisms under high torque applications. More extensive use of back-up mechanisms designed into the primary mechanism such as the JPL dual drive design (an excellent example of good design practice).

Self-propelled robots for assembly, sample-gathering, exploration. Thrustor-less robots using momentum control for propulsion. Mechanisms such as valves and position devices that operate at cryogenic temperatures. Extremely low-power dithering devices for guidance sensors.

Control moment gyros/reaction control wheels. Long life slip ring. Remote power/signal transfer by optical means.

Needs are established by specific requirements; mechanisms technology has been refined since the industrial revolution. It only needs to be adapted to specific spacecraft applications.

One time Deployables, and low shock separation devices are needed.

Long life, high accuracy, low friction bearings, particularly for oscillating motion.

- (1) Standardized autonomous spacecraft rendezvous and Martin docking system using state-of-the-art technology for a long operating life. Includes electrical, fluid and gas connectors.
- (2) Standardized orbital replacement unit interface mechanism with electrical, fluid and gas connectors. Mechanism uses state-of-the-art technology for a long operating life.
- (3)

Standardized family of spacecraft latch mechanisms for a long operating life. Latches capable of restraining a variety of spacecraft components. (4) Standardized antenna deployment and gimbal actuator mechanisms. (5) Standardized precision pointing rotary actuator with high stiffness and zero backlash. Includes lubrication system for actuator gear train. (6) Standardized satellite attachment device to aid in satellite retrieval. (7) Standardized spacecraft berthing mechanisms. (8) Standardized hatch mechanism for astronaut habitation modules. (9) Advanced precision actuators for space manipulator arms. (10) Standardized end effectors for space manipulator arms, includes electrical interface connectors. (11) Standardized tools for space manipulator arms. (12) Solar array deployment and pointing rotary actuator mechanisms. (13) Sensors such as potentiometers, resolvers, encoders or advanced position sensors. (14) Actuator/isolator pointing systems. This pointing system would be used to point optical devices such as telescopes, lasers, etc., minimizing disturbances from the spacecraft.

Improved lubrication for controlled moment Gyro (CMG) ball bearings - perhaps hard coatings. Improved lubrication for harmonic drive gears and bearings.

Increased level of autonomous operation. Need for smarter mechanisms. Low power magnetic isolation. Highly damped large structures. Mechanical isolation systems. Long term commitment to an IR&D program that has direction. This has to be outside the changing political climate and be product focused, not project oriented.

Mechanisms or systems for the management, transfer, etc. of cryogenics in space. Development of self-contained life support systems. Robotic systems as well as automatic devices. There is no reason to reinvent the wheel. A major effort should be made to adapt existing mechanisms for space applications.

Electrical Commutators. Active methods of thermal control and further evolution of heat pipe technology. More power-efficient motors. Power transmission schemes that do not use gears and innovations in gear metallurgy and lubricants. Active methods of controlling structural deformations.

Space mechanisms must be friendly to robotic systems, allow for human errors, versatile in design, capable of auto-latch and quick change, functionally dependable, and durable in hostile space environments.

Power linear actuators. As payloads get larger, required response times become shorter, the demand for power actuators will increase. To excavate lunar soil will require a substantial increase in power actuators and the ability to dissipate the heat. A better dry film lubricant.

Non-metallic self-lubricating Bearings, more approved GE manufacturers of actuators to bring down cost. Aid smaller vendors in designing and qualifying space flight components. Stepper motors running at high pps (>400) without torque rolloff or operation degradation. Design to requirements not to mil-spec xxxx, too conservative/costly design otherwise.

(1) Robotics at the space station, (2) Seal technology could be improved with respect to materials.

(1) High reliability actuators both rotary and linear and their power systems which do not utilize electrical power. Prefer a stored energy gas system. (2) Development of credible mechanical field failure rate.

Dr. Bean of PRC under contract to NASA-KSC developed both technique and a data base for mechanical failure rate for ground support equipment. Both a technique and a handbook need to be developed for space mechanisms with coverage for maintained v.s. non-maintained systems and for active v.s. dormant systems. This subject has been a major disappointment for those of us who started the Reliability and Maintainability Symposium. This project never got off the ground winning support within government or contractor organizations. A major impact such a handbook would have beside design is support in the development of logistics and resupply.

(1) Mechanical Components - More precise encoders for higher precision control and more reliable, long life flexural pivots with quantified low temperature performance. (2) Bearing Development - Lightweight no-contact magnetic bearings, higher toughness ceramic and ceramic matrix composite materials, (3) Lubrication - Specific vacuum friction-wear performance data and mechanisms for additive modified fluid lubricant - bearing material combinations, new solid lubricants with greater densification, higher stress capability and endurance lifetimes, and better analytical modeling capabilities on effects of hard and solid lubricant coatings on stress reduction and re-distribution.

I think we will need more accurate pointing systems. Two areas come to mind immediately, laser communication and the study of astronomy. In both cases mirrors or entire telescopes need to be pointed very accurately for a long time period. We need to quantify what can be done with rolling element bearings, and decide how to go past the areas these bearings can achieve. I believe an active lubricant recovery and recirculating system (not sealed) can be developed and would be useful in lubricating conventional bearings and also in developing hydrodynamic lubrication.

Long Life with not Lubricants, need very clean optics.

Highly reliable, long-life drive mechanisms

Slide bearings for cast aerospace metals.

Thirty year life for rolling and sliding mechanisms: coatings, platings, solid lubricants.

How about magnetic bearings; they will eliminate lubrication and wear problems. In space these need not necessarily require too much power to activate them, especially those mechanisms where motion is intermittent and of short duration.

More erosion resistance surfaces. Thin self-replenishing coatings to deter asperity adhesion. Materials (probably oxide ceramics) that avoid excessive adhesive wear in the absence of an oxidizing atmosphere.

(1) Development of self-lubricating solid materials with structural strength of long-lasting coatings to meet tribology requirements. (2) development of boundary lubrication technology for space applications. (3) Development of fluid-film (liquid or gas) lubrication technology and related sealing technology for space applications. (4) Tribology is a link or an aspect of the over-all system. Some tribology problems can be solved through novel designs of mechanisms. I see the general need for developing a new design philosophy for space applications.

Surface engineered tribo-components specifically for vacuum environment.

Next generation RWA/CMG/MWA design and development: - minimum weight, - low power, - ball bearing vs magnetic suspension, - composites as structural materials, - lubricants.

Deployable multi-bar linkages, low friction mechanisms, non-deteriorating long term lubricants.

Light weight Latching, releasing mechanisms for stowing and later deploying structures or equipment.

Many designers are faced with designing mechanisms which are required to operate in a hard vacuum. As aluminum is the material of choice, data on variation of friction coefficient for aluminums and associated coatings (chemical films, anodized, hard anodized, dry-film lube) with respect to time at vacuum and level of vacuum as well as temperature is needed. Extensive literature searches have not been successful.

Minimum to a zero wear capabilities. Prevention of galling, scoring. Self-healing of the scored areas.

Depends on the program's needs, and as you can see I have no faith in NASA's ability to develop good programs, keep them "sold," and build on these programs in an evolutionary manner.

Here are some, in no particular order:

1. Low torque noise, long lived and environment resistant gimbal bearings.
2. Backlash free, stiff, low torque jitter, light and long lived drive reducers and actuators.
3. Vibration free, low power consumption, reliable cryocoolers for infrared sensors.
4. Long lived, quiet momentum wheel spin bearings for large CMG's and gyro spin bearings for inertia maneuvering units.
5. Lower weight, shockless deployment actuators.
6. Stiffer, less complex extendable booms.
7. Improved power, data fluid rotating utility-transfer devices.
8. Atomic oxygen and radiation tolerate, low outgassing, low debris formation, long lived, boundary space lubricants.
9. Light weight materials and tribological coating processes for space gears and rail sliding mechanisms.
10. Simpler, lighter and more reliable launch-lock, off loading mechanisms.
11. Stiff, light-weight mechanism structures having high internal damping.
12. Improved solar arrays and attendant mechanisms for large space power generation.
13. More autonomous mechanisms for space stations maintenance and satellite retrieval.
14. Ultra-precision, positioning mechanisms for sensor payload pointing, scanning and/or tracking.
15. Distributed actuator mechanisms for controlling long flexible structures.

- Exotic material research and standardization
- Organization and distribution of existing technology
- Added support for existing programs such as the Aerospace Mechanisms Symposia and NASA Tech Briefs.
- Metric fastener standards and sources

Passive Isolators with quickly adjustable stiffness and damping characteristics

- a) high temperature (>1200K) lubrication for stepping-type motors
- b) non-weld piping connections with zero leakage

All associated with surface finish and tribology needs for space station mechanisms. We at Astro are designing the mobile transporter for Space Station for a 30 year lifetime with maintenance.

- PV array structures (deployable and erectable), mobile and stationery
- High pressure H₂ & O₂ gaseous storage (mobile and stationery)

"Non-contact" bearings - no wear

- 1) FTS and effectors of the future
- 2) Large space structures:
 - mechanized erection
 - deployable single launch type

The continuously rotating, 12 ft. diameter, solar alpha joints represent a unique design challenge and a significant space qualification effort for SSF. The sealed, cam follower type, trundle bearings require design consideration for lubrication life, lubrication replenishment and bearing replacement.

Long life maintenance free bearings for space mechanisms are certainly needed. Active controlled magnetic bearing, foil bearing, low-wear hydrostatic bearing, highly damped (with adequate damper such a piezo-ceramic damper) and solid lubricated ball/roller bearing are a few of the examples.

Permanent non-outgassing lubrication

Space station hatch latch mechanism. Some unused airlock ports may remain exposed to vacuum without being operated for years, then be required to work.

Ceramic and (ceramic balls, steel races) hybrid ball bearings. To eliminate lube requirements and to still operate after years of dormancy. Adhesive development to join ceramic and steel, or other, and act as a buffer through the thermal excursions and inequities.

I believe that ceramic materials can be utilized in many instances where "fretting corrosion" would be a problem for metals. However, the use of ceramic materials, and the data on it's behavior and characteristics, have not been widely published.

Better methods for passive low costs structural damping. Better low cost isolation systems. Active systems for large complex systems are themselves too complex & costly.

- 1) Development of simple aerospace mechanisms that can function reliably in the space environment for >10 years:
 - (a) subject to thermal cycling, radiation, debris impact, plume impingement, but...
 - (b) durable materials and lubricants
 - (c) simple means of redundancy
 - (d) low infant mortality (start up)
 - (e) mechanisms that can be simplified and manufactured at longer expense (or have a lower life time operational expense)

(f) simple mechanisms that can integrated together to perform complex tasks.

Space station

Long life gimbals (bearings)

Long life slip rings

Long life seals

For all space mechanisms

I took the liberty of sending a copy of this questionnaire to both Harmonic Drive and Carolina Coating Technologies, Inc. who is the supplier of Diamond Black Coatings. In addition, I spoke with Honeywell Space & Aviation Systems of Durham, NC who also received a copy of this questionnaire directly. They are better able to answer this question.

Improvement/advancement in QD technology - especially remote/robotic handling and coupling. Design/development of a swivel-end fitting for flex hoses that would allow rotation about its longitudinal axis without leakage. Need data on flex resistance of flexible metal hoses, bellows and gimbals.

Future

- (1) Alloys for long duration missions.
- (2) Propulsion systems
- (3) Lunar habitats, construction and maintainability
- (4) Lunar launch facilities/landing-docking facilities

Current

- (1) Shuttle brakes and tires
- (2) Launch interface hoses and cabling shielding/hardening
- (3) Payload bay generic configuration pallet for launch/retrieval use that can be reconfigured in flight for satellite retrieval
- (4) Processing and launch facilities access platforms, increased mobility.

Development of following mechanisms is essential:

1. All mechanisms necessary for assembly/disassembly/maintenance in 0-g, low intensity broad band light, high intensity broad band light environments
2. All mechanisms necessary for waste disposal (biological, mechanical, chemical)
3. All mechanisms necessary for evaluation of environmental parameters as modified by understanding of space influence.
4. All mechanism necessary for EVA in environments qualified by LDEF and other results.

Long term storage tests, more redundancy, replaceability, serviceability, life tests

Long life gimbal and spin bearings.

Higher precision gimbal bearings.

APPENDIX

RESPONDERS TO QUESTIONNAIRE

NASA

Julio C. Acevedo	NASA LeRC
H. W. Adams	NASA-LaRC
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OTHER GOVERNMENT

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Stephen Hsu	NIST, DOE
Dan Kuban	Oak Ridge Nat Lab
B. D. McConnell	Air Force Mat Lab
Bill Purdy	Naval Res Lab

INDUSTRY AND UNIVERSITIES

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Joseph M. Cardin	Moog, Inc.
J. P. Cardin	Moog Inc.
Dr. M. Chew	Old Dominion Univ
Ron Christy	TRW
R. H. Coco	C.S. Draper Labs
John DeAngelis	Martin Marietta
M. E. Donahue	Lockheed
T. S. Dempsey	S&Q Corporation
Keith DuFrane	Battelle
V. Dunaevsky	Copeland Corp
Otto H Fedor	Aerospace Mechanisms Advisory Board
B. C. Feng	Lockheed
W. C. Fincher	SBRC
Richard Fink	Honeywell
Ed Fisher	Boeing Aerospace
Donald G. Flom	Retired GE
Frank A. Folino	MIT-Lincoln Labs
Stephen Gorevan	President, Honeybee Robotics
Chris Grainger	General Dynamics
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Laurence Gresko	Hughes
Russell Hacker	Stanford Univ
Robert A. Hanson	Miniature Precision Bearings
James W. Harris	Martin Marietta
Sam Harris	Odetics, Inc
Martin Hasha	Lockheed Missiles & Space Co.
J. W. Kannel	Battelle Labs
Steven King	Lockheed Eng. & Sciences
D. J. Koi	Aerospace Corp
Frank Kustis	Martin Marietta
H. L. Lamberth	Lockheed, FL
K. W. Lang	Rocketdyne
Stuart Loewenthal	Lockheed Missiles & Space Co
M. J. Madden	?
G. W. Marks	Astro Aerospace Corp.
W. D. Marsher	Dresser Pump Div
David S. McCann	NASA JSC/Lockheed
Crawford Meeks	Avcon
R. Meschen	ITT-Aerospace
D. L. Miller	Lockheed
Dean Monitor	Martin Marietta
Walter E. Nestvogel	The Larmax Group
Ted Nye	TRW
Barry O'Dwyer	MPB Corp.
Scott Orlosky	TiNi Alwy Co
D. C. Parker	Lockheed
Adam Pinty	Cleveland St. University
Robert Renken	Ball Aerospace
Wilf Robinson	Honeywell, Inc
K. G. Roller	Ball Aerospace
Anthony Rosinson	GE Astro-Space
M. Saville	AiResearch, LA
W. G. Smith	look up
M. R. Snodgrass	Martin Marietta
Pat Spurlock	Precision Castparts
David Stubbs	Lockheed Research
D. C. Sun	State Univ of NY
J. L. Tevaarwerk	Battelle Labs
David Thrasher	Boeing
Tom Tourville	Santa Barbara Research Ctr, GM/Delco
F. B. Van Shoubrouek	McDonnell-Douglas
Robert M. Warden	AEC-Able Engineering Co.
Vern Wedeven	Wedeven Assoc.
Jerry V. Wood	TRW
Robert O. Woods	Sandia Natl Labs

LETTER SENT TO GOVERNMENT AND INDUSTRY PERSONNEL

5200

February 22, 1990

^F1^

Dear ^F2^:

In his speech on July 20, 1989, President Bush asked Vice President Quayle to lead the National Space Council in determining what is needed to chart a new and continuing course to the Moon and Mars and beyond. In support of this endeavor, NASA Administrator Richard H. Truly created a task force to conduct a 90-day study of the main elements of a Human Exploration Initiative.

The results of that study are now complete. The Task Force concludes: first the Space Station Freedom, next back to the Moon, and then a journey to Mars. The general mission objectives and key program and supporting elements of these missions have thus been defined. Regardless of the implementation approach, the following systems will be required: heavy launch vehicles, space-based transportation systems, surface vehicles, habitats, and support systems for living and working an extraterrestrial environment.

All these missions will require advanced mechanical moving systems. There is some concern at NASA that the current state-of-the-art may not be adequate to meet the performance, life and reliability requirements that these missions will require. Because of this perceived need, Sam Venneri, Director of NASA Headquarter's Materials & Structures Division of the Office of Aeronautics and Space Technology, is forming a Steering Committee composed of experts from various NASA and DOD centers to assess the need for expanding our technology research in space mechanisms (mechanical components/tribology).

In order to provide input to the committee, Sam has asked me to solicit viewpoints from government and industry people working in the field of space mechanisms. To accomplish this, I have prepared a questionnaire and ask if you could fill it out and send it back to me in the enclosed stamped, self-addressed envelope as soon as possible. Thank you in advance for your help!

Sincerely,

Robert L. Fusaro
Structures Division

QUESTIONNAIRE ON CURRENT SPACE MECHANISMS TECHNOLOGY

1. It appears that the current state-of-the-art of space mechanisms (mechanical components/tribology) is not adequate to meet new, long duration, future NASA Space Missions such as the space station "Freedom"(a 30 year life), a Lunar Outpost, and unmanned or manned Martian Missions.

Do you agree? Yes_____ No_____. Reasons for answer?

2. Is there a need for new or improved space mechanisms (mechanical components/tribology) technology development?

Yes_____ No_____ Reasons for answer?

3. What would be the benefit of a coordinated space mechanisms technology program? How would you benefit from such a program?

4. Do you feel there is a need for NASA to establish a Space Mechanisms Technology Infrastructure in order to:

- Coordinate new technology development.----- yes____ no____
- Develop standards for U.S. Industry use.----- yes____ no____
- Furnish consultancy and advisory services.----- yes____ no____
- Maintain a comprehensive data base on capabilities/solutions.-- yes____ no____
- Maintain adequate testing facilities for U.S. Space interests.---- yes____ no____
- Facilitate the transfer of space technology.----- yes____ no____
- Encourage crosstalk between government customers.----- yes____ no____
- Insure coordination of NASA and DOD research.----- yes____ no____

Reasons for Answers? Should any areas be added or deleted to the above list?

5. What kind of space qualification techniques (e.g. accelerated testing methods) need development.

6. What are some specific current or anticipated Space Mechanisms needs.

Name _____ AFFILIATION _____



National Aeronautics and
Space Administration

Report Documentation Page

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15. Supplementary Notes Responsible person, Robert L. Fusaro, (216) 433-6080.					
16. Abstract President Bush has proposed that the United States undertake an ambitious mission of manned and robotic exploration of the solar system. This mission will require advanced mechanical moving components, such as bearings, gears, seals, lubricants, etc. There has been concern in the NASA community that the current technology level in these mechanical component/tribology areas may not be adequate to meet the goals of such a mission. To attempt to answer this, Lewis Research Center has sent out a questionnaire to government and industry workers (who have been involved in space mechanism research, design, and implementation) to ask their opinion if the current space mechanisms technology (mechanical components/tribology) is adequate to meet future NASA Missions needs and goals. If they deemed that the technology base was inadequate, they were asked to specify the areas of greatest need. This paper presents the unedited remarks of those who responded to the survey.					
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